AMERICAN SOCIETY OF CIVIL ENGINEERS.
INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

723.

(Vol. XXXII.—August, 1894.)

FRICTION ROLLERS.

By C. L. CRANDALL, M. Am. Soc. C. E., and A. MARSTON, Assoc. M. Am. Soc. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

WITH DISCUSSION.

PART I.

By C. L. CRANDALL, M. Am. Soc. C. E.

In 1886, the College of Civil Engineering, Cornell University, had a set of plates and rollers made for experimental purposes. The plates were about 1½ ins. thick and 5 ins. wide, and the rollers were 1, 2, 3 and 4 ins. in diameter, all 1½ ins. long, except the first, which were 1 in. long; there being a full set of plates and rollers in cast iron, in steel and in wrought iron.

Mr. C. B. Wing, now Professor of Structural Engineering, Leland Stanford University, undertook the determination of rolling friction for his graduation thesis. Three horizontal plates were put into the testing machine and separated by two parallel rollers, one above and the other below the middle plate; a third roller was placed under the middle plate, to steady it, although receiving but little load.

The force required to produce sensible motion of the middle plate was measured with a spring balance for different loads on the testing machine, and one-half of this force divided by the load was taken for the friction of rest per unit load. The rollers and plates were taken as they came from the tools of the lathe and planer without polishing or filing.

For the 1-in. rollers six different loads were applied, ranging from 350 to 900 lbs., and two determinations were made for each load for each combination of materials, except for the cast-iron rollers, for which only one determination was made for each load. The friction per unit load does not appear to vary with the load, although the individual results vary considerably.

For the 2-in. rollers 12 different loads were applied, ranging from 600 to 2 300 lbs. per lineal inch of roller, with two determinations for each case and apparently no variation with load.

For the 3-in. rollers 12 different loads were applied, ranging from 760 to 2 350 lbs. per lineal inch, with two determinations for each case and a slight tendency for the friction per unit load to increase with the heaviest loads.

For the 4-in. rollers 12 different loads were applied, ranging from 830 to 2 500 lbs. per lineal inch, with two determinations for each case, and with apparently no variation with load.

The unit friction is affected somewhat by the plate, it being 13% greater for the wrought iron and 13% less for the steel than for the cast iron.

The friction is so much affected by the rollers that the values will be given separately for the cast iron, wrought iron and steel.

The usual formula is—

$$P = \frac{b}{r} G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where P = resistance applied at the center of the roller or wheel; r = radius; G = weight; b = the "coefficient of friction" = the distance the point of support is moved forward by the yielding of the material.

According to the extensive experiments of Morin upon the resistance of wagons upon roads, b is independent of r; according to those of Dupuit, and the more recent ones of Poirée and Sauvage, by means of railroad cars, b varies as $\sqrt{r}$; in the one case P varies as $\frac{1}{r}$, and in the other as in $\frac{1}{\sqrt{r}}$.

The exponent of r being thus uncertain, the formula was put in the form—

Friction per unit load $\frac{P}{G}$, or $F = \frac{b}{r^a}$, or

$$\text{Log. } F = \log. b - a \log. r \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The experiments give the following values for F:

r	F		
	Cast rollers.	Wrought rollers.	Steel rollers.
0.5"	.0082	.0138	.0075
1	45	82	47
1.5	32	63	45
2	31	69	....

These values substituted in (2) will give four observation equations for each material from which to determine the most probable values of a and b. The ordinary method of least squares gives—

$a = 0.75$; $b = .0079$ for cast rollers; $a = 0.55$; $b = .0130$ for wrought; $a = 0.55$; $b = .0073$ for steel.

The formula thus becomes—

$$\text{Friction per unit load} = \frac{.0079}{r.^{75}} \text{ for cast rollers.}$$

$$\text{“ “ “} = \frac{.0130}{r.^{55}} \text{ for wrought rollers.}$$

$$\text{“ “ “} = \frac{.0073}{r.^{55}} \text{ for steel rollers.}$$

These nearly conform to the $\sqrt{r}$ formula. Changing to that form we have—

$$\left.\begin{aligned} \text{Friction per unit load} &= \frac{.0063}{\sqrt{r}} \text{ for cast rollers;} \\ \text{“ “ “} &= \frac{.0120}{\sqrt{r}} \text{ for wrought rollers;} \\ \text{“ “ “} &= \frac{.0073}{\sqrt{r}} \text{ for steel rollers.} \end{aligned}\right\} \quad \ldots\ldots\ldots (3)$$

For wrought-iron plates these values should be increased about 13%, and for steel plates decreased by the same percentage.

If these formulas could be extended to the 20-in. cast wheel, rolling upon a cast track, experimented upon by Weisbach and Rittinger (Weisbach's “Mechanics,” Vol. I, page 354), they would give the friction

per unit load .0020 instead of .0018, as found by the former, and .0019, as found by the latter. If extended to the 39.4-in. railroad wheels of Pambour (assumed to be wrought iron on wrought-iron rails), they would give the friction per unit load .0027, instead of the .0100 to .0110 actually found by him. The formulas (3) thus give too large a result in the first, and too small a one in the second case, when extended to radii very much greater than those experimented upon, which would not suggest a change in the exponent of r if it is to remain the same for cast and wrought iron.

The next academic year, 1886–87, Mr. Wing, as Fellow in the College, and the writer undertook a series of wearing tests upon these rollers and plates in order to determine the life of rollers for different loads and materials. They were placed in the testing machine with one roller between the upper and middle plates, and two between the middle and lower, their axes all parallel; the full load on the upper roller was thus divided between the two lower ones. The center plate was driven back and forth about $\frac{3}{4}$ in., rotating the rollers, by means of a small water wheel acting through a connecting rod upon a rod working in guides and attached to the plate by a flexible joint. The number of turns of the crank was registered by an attached odometer. The scale beam was kept balanced at a constant load during the experiment. Motion was continued until the surfaces were injured by wear, but it was found impossible to reach the same degree of wear with all, first on account of the difficulty of examining the surface until the experiment was stopped and the rollers removed, and second, on account of the long time required to produce wear with the lighter loads.

The wearing effect was towards a gradual rusting of the surface, which changed to a blackening, accompanied with black dust of worn-out material as the wear increased; finally, pitting of the surface took place, with a flow of metal at the ends of the rollers and around the edge of the contact portion of the plate. The results are given in the table on the opposite page.

The elastic limit in compression of a short steel rod about 1 in. in area, cut from the rod which furnished the smaller rollers, was found to be 46 000 lbs., and the modulus of elasticity 31 500 000 lbs. The cast iron gave an elastic limit in a short length of 41 000 lbs., an ultimate of 100 000, and a modulus of elasticity of 14 400 000 lbs., all in compression.

Wear of Rollers.

Date.		Odometer revolutions.	Load per lineal inch of roller.	Roller.	Plate.	Condition of Worn Surface.	
						Roller.	Plate.
1886.	Sept. 16th to Oct. 18th.	299 168	1 510	Wrought iron..	Cast iron	Pitted considerably	Pitted slightly.
			910	2" diameter	1.47" thick.....	Blackened.....	Blackened.
			600	1.5" long.....	"	Slightly blackened	Slightly blackened.
	Nov. 1st to Dec. 4th.	233 174	1 890	Wrought iron..	Cast iron.....	Pitted badly, flow of metal at ends.....	Pitted considerably.
			1 240	3" diameter	"	Beginning to pit	Beginning to pit.
			650	1.5" long.....	.....	Blackened.....	Blackened.
	Dec. 8th to Jan. 6th.	423 292	2 270	Wrought iron..	Cast iron.....	Pitted slightly	Pitted slightly.
			1 400	4" diameter	"	Blackened, beginning to pit.....	Blackened, beginning to pit.
			670	1.5" long.....	.....	Blackened	Blackened.
1887.	Jan. 8th to Feb. 21st	806 483	2 270	Cast iron	Cast iron.....	Blackened	Blackened.
			1 500	4" diameter....	"	Rusted, part blackened	Blackened.
			770	1.5" long.....	.....	Rusted.....	Rusted, part blackened.
	Mar. 2d to Mar. 29th	631 642	4 530	Cast iron.....	.....	Blackened, beginning to pit.....	Blackened, beginning to pit.
			2 330	4" diameter....	Cast iron.....	Blackened, beginning to pit at one end...	Blackened, beginning to pit at end.
			2 200	1.5" long.....	"	Blackened.....	Blackened.
	April 2d to April 9th	361 154	3 940	Cast iron	"	Blackened, beginning to pit.	
			1 970	3" diameter....	"	Blackened and rusted.	
			1 970	1.5" long.....	.....	Rusted.	
	Apr. 26th to May 7th.	277 165	3 260	Cast iron.....	Cast iron.....	Pitting begun.....	Plates show more wear than rollers.
			1 960	2" diameter....	"	Blackened, beginning to pit.	Plates show more wear than rollers.
			1 300	1.5" long	.....	Rusted.	
	Oct. 21st to Nov. 2d.	242 033	3 260	Steel	Cast iron.....	Top blackened; bottom deeply pitted; flow of metal at one end.	
			2 290	2" diameter....	1.41" thick.....	Blackened, beginning to pit.	
			970	1.5" long	5" wide	Blackened in streaks.	
	Nov. 7th to Nov. 12th	122 755	2 130	Steel	Wrought iron..	Deeply pitted; flow of metal at ends.....	Deeply pitted.
			1 520	2" diameter....	1.47" thick.....	Blackened, beginning to pit.....	Blackened, beginning to pit.
			610	1.5" long.....	.....	Rusted.....	Rusted and blackened.
	Nov. 15th to Dec. 1st.	354 145	2 130	Cast iron.....	Wrought iron..	Slightly pitted	Slightly pitted.
			1 650	2" diameter....	" ..	Blackened, beginning to pit.....	Blackened, beginning to pit.
			480	1.5 long.....	.....	Rusted.....	Rusted.
	Dec. 1st to Dec. 9th.	138 580	2 130	Wrought iron..	Wrought iron..	Slightly pitted	Pitted.
			1 160	2" diameter	" ..	Pitted.....	Pitted.
			970	1.5" long.....	.....	Blackened and rusted.....	Blackened and rusted.
	Dec. 9th to Dec. 30th	468 088	2 130	Steel	Steel.....	Blackened.....	Blackened, one end polished.
			1 090	2" diameter....	.....	Rusted.....	Rusted.
			1 040	1.5" long.....	.....	Rusted and blackened.....	Rusted and blackened.

It is not felt that these experiments will give more than a hint at the effect of diameter, load and material upon the wear of rollers; but they may serve as a nucleus about which to collect the results of others, both from the field and laboratory.

In order to determine what a certain number of revolutions of the odometer means with reference to the life of a bridge roller, observations were taken upon a Lehigh Valley Railroad bridge of some 100-ft. span over Fall Creek at Ithaca, during the passage of slow-moving freight trains, and upon a Delaware, Lackawanna and Western Railroad bridge over the Chemung, near Waverly, during the passage of faster freight trains. Both bridges had been recently erected. The first was a through bridge upon masonry abutments. The roller end moved out when the train entered, and back when it passed off, with no vibration or other motion for the ordinary short trains of that branch of the road. The second was a deck double-track bridge of some 160-ft. span, with the fixed end upon a masonry abutment, and the roller end upon a masonry pier, 7.5 ft. wide at the top and some 25 ft. high above the stream. The roller end vibrated considerably, but most of the vibration was transmitted to the pier without moving the rollers. One short train of an engine and two cars gave a motion of the rollers out and back, with some eight vibrations of about $\frac{1}{10}$ in. each. Three long freight trains gave three motions out and back each, with no vibration of sufficient amplitude to be recorded on the self-registering apparatus.

For medium spans on heavy traffic roads, it is believed that 10 motions per train is not above the actual. This would correspond to an odometer reading of 73 000 per year for a road of 10 daily trains each way, requiring but a very few years to reach the numbers in the above table, without allowance for the dirt and rust of the actual bridge rollers.

During the next academic year, 1887–88, experiments were made to determine the effect of load and diameter upon the area of contact between the roller and plate, and also to find the elastic limit, in order to test the Grashof roller formula. The same rollers and plates were used as in the experiments already described. The results have been discussed by Professor Marston in connection with this paper, and need not be repeated here.

The Grashof formula not being satisfactory theoretically, and not

giving results agreeing with experiment, it was felt that valuable data in regard to the actual distribution of stress in the roller could be obtained by examining a glass roller under stress by means of polarized light. Accordingly, the college purchased a 1-in. and a 2-in. roller of optical glass of Brashear. No one was found to take up this portion of the work until Professor Marston came to the college for graduate work during his own vacation in December, 1892. A cube of optical glass was added, and suitable apparatus placed at his disposal for carrying on the work, which was begun at Cornell and completed at Ames, Ia. He also extended and supplemented the metal roller contact experiments, as more fully described in the able paper given as Part II.

PART II.

By A. MARSTON, Assoc. M. Am. Soc. C. E.

The investigation described below was begun in the winter of 1892–93 at the suggestion of Professor Charles L. Crandall, of the College of Civil Engineering of Cornell University, whom the writer had assisted while a student at the University in 1887 and 1888, in making a series of tests of bridge rollers. The material for the experiments with polarized light described below was supplied by Cornell University, at which the writer was spending part of a vacation when the work was begun. The investigation has been continued at such times as he could spare from his regular duties. The writer desires to acknowledge here his indebtedness to Professor W. S. Franklin, of the Department of Physics, Iowa State Agricultural College, for assistance in developing the method of studying strains by polarized light.

The fact that stressed glass bodies exhibit striking optical effects when viewed by polarized light has long been known, and the exhibition of these effects is one of the standard experiments of the physical lecture-room. Previous attempts, also, have been made to utilize these effects in the study of stresses. Wertheim long since invented a device by which he used the colors of polarization in determining the intensity of stress uniformly applied,* and Mr. Louis Nickerson, M. Am. Soc. C. E. (deceased), attempted to determine the position of the neutral axis in beams by experiments with polarized light.† Mr. Nickerson's interpretation of his results, how-

* See *Comptes Rendus* 32, page 289 (1851), and *Phil. Magazine* (4) 8, page 241 (1854).
† See *Transactions*, Vol. III, page 31.

ever, was based upon a misconception of their true meaning. Since writing this paper, the attention of the writer has been called to the fact that Professor C. A. Carns Wilson published an article in the *Philosophical Magazine* for December, 1891, entitled "The Influence of Surface Loading on the Flexure of Beams," which gives the lines of stress as found experimentally by polarized light. The method used by the writer in this work was described in the *Physical Review* of Cornell University for September–October, 1893.

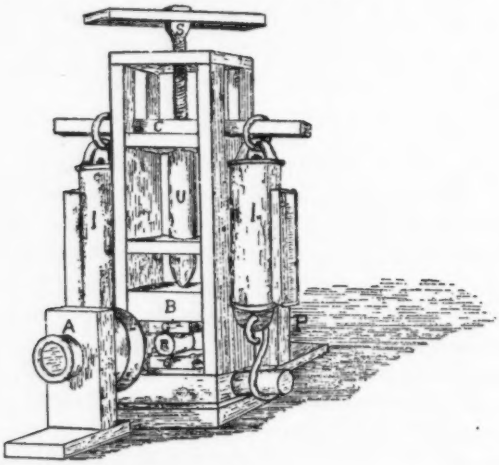
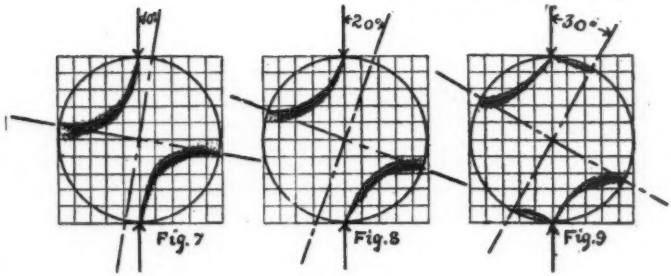


Figure 1.

The use of this method in the study of the distribution of the stresses in a bridge roller will be better understood after the apparatus used in the experiments has been described. This apparatus is shown in Fig. 1. By means of the screw *S* working in the steel cross-piece *C*, pressure was applied to the upright pin *U* and thence to the loose block *B*, and glass plate *G'*. Between this plate and another *G''* the roller to be examined was placed. *U* had a ball-bearing on *B*. The amount of the pressure was measured by the sum of the readings of the two ice scales *I*, *I*, plus the weight of *B*, *U*, *C*, *S*, and *I*, *I*.

The analyzer *A* was a Nicol's prism set in a brass tube in the usual manner, and for these experiments mounted in an upright block of wood as shown in the figure. By means of a graduated paper strip



LINES OF STRESS BY POLARIZED LIGHT.

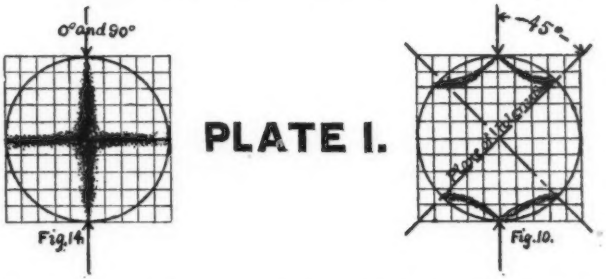
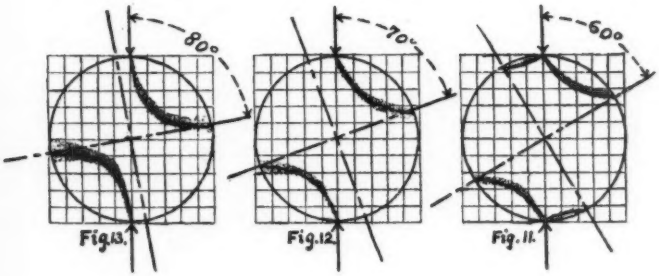


PLATE I.

Diameter of Roller, 1in; Length, 1in; load, 400lbs.



pasted on the brass tube, the plane of polarization could be set (within a degree or two) at any desired angle with the vertical. The polarizer *P* (mostly hid from view by the other parts of the apparatus in the figure) was a similar Nicol's prism, similarly mounted.

The two rollers studied by this apparatus in these experiments were of optical glass, 1 in. long, and respectively 1 in. and 1.98 ins. in diameter. The ends were polished, and the cylindrical surfaces ground true. The rollers were made by Brashear, of Pittsburgh, Pa. They bore above and below against pieces of plate glass $1\frac{1}{2} \times 1 \times \frac{1}{3}$ ins.

When the planes of polarization of the polarizer and analyzer were set at right angles to each other (prisms crossed), and the observer looked through the analyzer at the end of the roller, the following phenomena were observed: With no load on the roller the whole of its face was dark; with a load (of 200 lbs., say) on the roller, the light was restored over most of the face of the roller, but there still remained dark bands, which moved when the prisms were rotated. There were also color bands which varied as described below.

When the planes of polarization of the polarizer and analyzer were set parallel (prisms parallel), the roller was clear in the unstressed condition, and only color effects were observed when the roller was loaded. The colors were in bands of yellow, red and blue (see Plates XVI and XVII) and varied in position as the load changed, and in brightness (though not in position) as the prisms were rotated.

In the article in the *Physical Review*, already referred to, it is shown that the dark bands seen when the prisms are crossed give the loci of the points where the lines of stress are parallel or perpendicular to the plane of polarization of the polarizer *P*, while the colors observed give the differences between the principal stresses, at the points where they are observed, according to the table on page 108.

Thus polarized light affords a means, first, to determine the lines of stress throughout the roller, and second, to check the intensities of the principal stresses as given by the formulas of any solution of the equations of elasticity for this case. In order to obtain these results a systematic series of observations of the dark bands and color bands was made for different loads for each of the rollers above described. To sketch the bands accurately, the face of the roller under observation was divided into $\frac{1}{10}$-in. squares by fine threads stretched in a brass frame, placed against the roller. The sketches were made on figures similarly divided, as shown in Plates XIV to XVII.

TABLE No. 1.

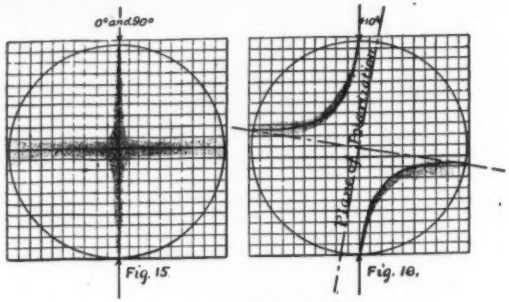
DIFFERENCES BETWEEN PRINCIPAL STRESSES CORRESPONDING TO THE COLORS OF POLARIZATION IN ROLLERS 1 IN. LONG.

Color.	Difference.	Color.	Difference.
Clear	100 lbs. per square inch.	Third red	2 550 lbs. per square inch.
Cloudy	200 " "	Green	3 000 " "
Faint yellow	300 " "	Fourth red	3 650 " "
Bright yellow	400 " "	Green	4 050 " "
First red	525 " "	Fifth red	4 750 " "
Blue	600 to 900 " "	Green	5 250 " "
Yellow	1 200 " "	Sixth red	5 900 " "
Second red	1 550 " "	Green	6 450 " "
Greenish blue	1 800 " "	Seventh red	7 050 " "
Greenish yellow	2 100 " "		

Plates XIV and XV show the dark bands observed under the loads stated on the plates, with the plane of polarization of the polarizer set at the angles with the vertical indicated on the figures, the prisms being crossed. For the sake of clearness, the color effects are omitted from these plates. Similar observations were made for loads of 100 lbs., 200 lbs. and 300 lbs., the results being the same as in the figures given.

Plates XVI and XVII show the color bands observed with the prisms parallel, under the loads stated on the plates. Each of the figures in these plates was made by combining the results of a series of observations with the plane of polarization of the polarizer set at different angles with the vertical, for in no one position of the polarizer could the color bands be seen throughout their whole extent.

A study of the results given in Plates XIV and XV, and of the observations made for the other loads (but not given here) showed that the position of the dark bands did not vary (except at the points of contact of the plates) for different loads. This showed that the lines of stress were the same for different loads. To determine the exact nature of the lines of stress, the case of the 1-in. roller sustaining a load of 400 lbs. may be taken. The dark bands for this case are given in Figs. 7 to 14, Plate XIV. The middle lines of these bands are grouped on one figure in Fig. 2, and show the angles of inclination of the lines of stress to the vertical at different points in the roller. Starting at any point on the horizontal diameter, as A, the line of stress through this point may be approximately drawn by first drawing a short vertical arc, then one inclined 5° to the vertical and extending nearly to



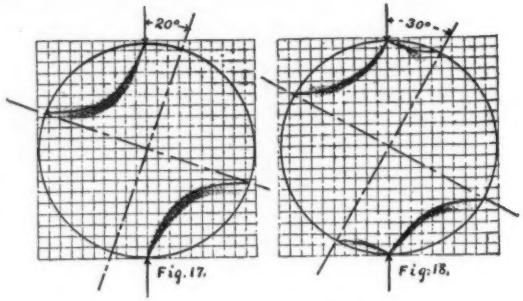
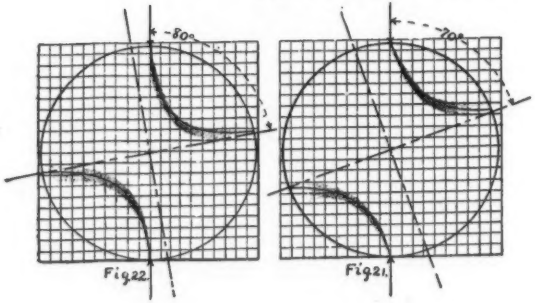


PLATE II. LINES OF STRESS BY POLARIZED LIGHT.

Diameter of Roller, 1.98 in. Length of Roller, 1 in. Load, 400 lbs.



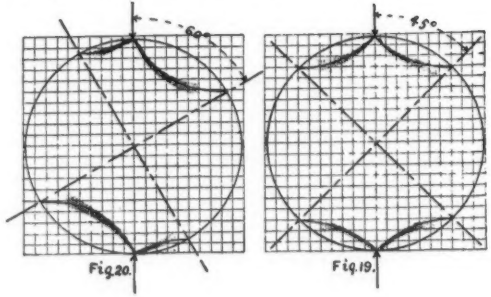


PLATE XV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 723.
MARSTON ON FRICTION ROLLERS.

the 10° line, then one inclined 10° to the vertical running past the 10° line, and so on. By repeating this process for different points, the lines of stress were found as shown in Fig. 2.

On trying these lines of stress with a pair of dividers, they seemed to be arcs of circles. To decide whether such be the case, the positions for the middle lines of the dark bands in Plates XIV and XV may be cal-

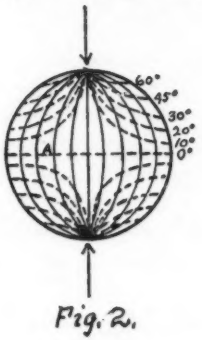


Fig. 2.

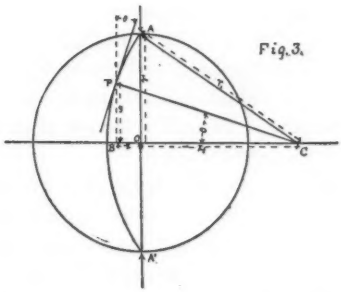


Fig. 3.

culated on this supposition and the results compared with the actual positions. The equation of the dark band corresponding to any angle Θ of the plane of polarization with the vertical may be found as follows: In Fig. 3 let P be any point of the dark band. The line of stress through this point makes an angle Θ with the vertical at P. Let the line of stress be an arc of a circle passing through A and A', and let C be its center. Then from triangle OAC—

$$r^2_1 = x^2_1 + r^2,$$

and from triangle PBC,

$$r^2_1 = y^2 + x^2 - 2xx_1 + x_1{}^2.$$

Hence, $r^2 = x^2 + y^2 - 2xx_1.$

But, $x_1 = y \cot. \Theta + x,$

hence, $r^2 = y^2 - 2xy \cot. \Theta - x^2,$

whence, $y = x \cot. \Theta \pm \sqrt{r^2 + x^2 \csc^2 \Theta}$ .....(1)

which is the required equation.

From this equation the lines which should coincide with the middles of the dark bands are platted on the figures in Plates XIV and XV. Inspection of the results shows that the lines practically coincide with the actual dark bands observed. Hence it may be considered as proven that the lines of stress in a bridge roller are, at least ap-

proximately, arcs of circles. A mathematical demonstration of this fact will be given further along, but it was first ascertained in the manner given.

The color effects shown in Plates XVI and XVII are very striking. If the stresses in the roller were simple stresses, these colors would give the approximate numerical value of the intensity of the stress at each point of the roller. The stresses, however, are in fact compound stresses, and what the colors do give is the differences between the principal stresses. Hence they will serve to check any theoretical solution of the problem of finding the stresses, but do not give data for forming the theory. To make use of these colors it was necessary, therefore, to attempt the solution of the general equations of elasticity for the case of the roller loaded as in the experiments, or as when under the end of a bridge.

In the solution of this problem the standard notation for stresses, displacements and constants of elasticity will be adopted, as follows:

At any point (x, y, z) in an elastic solid—

Let u = the displacement parallel to the axis of X;

v = " " " " " Y;

w = " " " " " Z;

P = normal stress on the plane perpendicular to the axis X;

Q = " " " " Y;

R = " " " " Z;

S = the shear tending to produce rotation about the axis X;

T = " " " " Y;

U = " " " " Z,

and let the subscripts p and r denote the stresses and displacements in the bearing plate and roller respectively. P, Q and R are $+$ for tensions. S, T and U are $+$ for shears tending to make the upper right-hand corner of a rectangular element acute, when *up* and *to the right* are the $+$ directions of the axes of co-ordinates.

Let μ = modulus of rigidity, $= \dfrac{2(1+\sigma)}{E}$

$$\lambda = \frac{E\sigma}{(1+\sigma)(1-2\sigma).}$$

E = Young's modulus of elasticity.

σ = ratio of lateral contraction to longitudinal expansion.

W = load per unit of length of roller.

r = radius, d = diameter, and l = length, of roller.

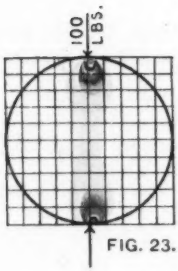


FIG. 23.

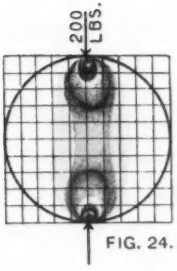


FIG. 24.

PLATE III

INTENSITY OF STRESS BY POLARIZED LIGHT.
1" ROLLER, 1" LONG.

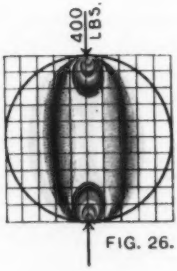


FIG. 26.

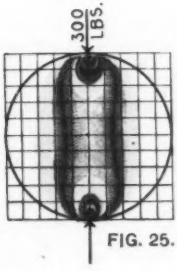


FIG. 25.

Also let $\triangle$ = the cubical dilatation, $= \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z}$, (where the character δ denotes partial differentiation) and let ∇^2 denote the operator, $\frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} + \frac{\delta^2}{\delta z^2}$.

Then, from Love's "Theory of Elasticity," page 76, the stresses are given in terms of the displacements by the equations—

$$\left.\begin{aligned} &P = \lambda\triangle + 2\mu \frac{\delta u}{\delta x}, \text{ with similar equations for } Q \text{ and } R, \\ &\text{and } S = \mu\left(\frac{\delta w}{\delta y} + \frac{\delta v}{\delta z}\right) \text{ with similar equations for } T \text{ and } U; \end{aligned}\right\} \quad \ldots\ldots(2)$$

And the fundamental equations of elastic equilibrium are

$$\left.\begin{aligned} (\lambda + \mu)\frac{\delta \triangle}{\delta x} + \mu \nabla^2 u = 0, \\ (\lambda + \mu)\frac{\delta \triangle}{\delta y} + \mu \nabla^2 v = 0, \\ \text{and } (\lambda + \mu)\frac{\delta \triangle}{\delta z} + \mu \nabla^2 w = 0. \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

The general problem of elasticity for any particular solid is to find systems of displacements and stresses which satisfy equations (2) and (3), and which at each point of the boundary of the solid give stresses equal to the components of the external load at that point.

The general problem of elasticity has been solved by Boussinesq, and also by Cerruti, for the case of a force parallel to the axis **Y**, acting at the origin of co-ordinates, on an infinite elastic solid, bounded by the plane $y = 0$. If the amount of the force be $W\,dz$, the resulting displacements are (see Love's "Theory of Elasticity," page 270)—

$$\left.\begin{aligned} u' &= -\frac{W\,dz}{4\pi(\lambda+\mu)} \frac{x}{h_o(y+h_o)} + \frac{W\,dz}{4\pi\mu} \frac{xy}{h_o^3}, \\ v' &= +\frac{W\,dz\,(\lambda+2\mu)}{4\pi\mu(\lambda+\mu)} \frac{1}{h_o} + \frac{W\,dz}{4\pi\mu} \frac{y^2}{h_o^3}, \\ w' &= -\frac{W\,dz}{4\pi(\lambda+\mu)} \frac{z}{h_o(y+h_o)} + \frac{W\,dz}{4\pi\mu} \frac{yz}{h_o^3}, \end{aligned}\right\} \quad \ldots\ldots\ldots (4)$$

from which the stresses P, Q, etc., can be computed by (2) above.

In equation (4) h_o = the distance from the point (x, y, z) to the origin of co-ordinates. Since the force $W\,dz$ must actually be applied over a small area instead of at a point, the solution holds true only for points at appreciable distances from the origin.

Now, suppose a load of length l, and of uniform intensity W per

unit of length, to press upon the infinite solid along the axis of Z, as in Fig. 4, giving a case similar to that of a bridge roller resting on a pier of the same material as the bearing plate, and let the origin be at the middle of the load (or roller). It is evident that the displacements and stresses at any point (x, y, z') of the solid will be equal to the integrals of (4), and of the corresponding stresses, between the limits

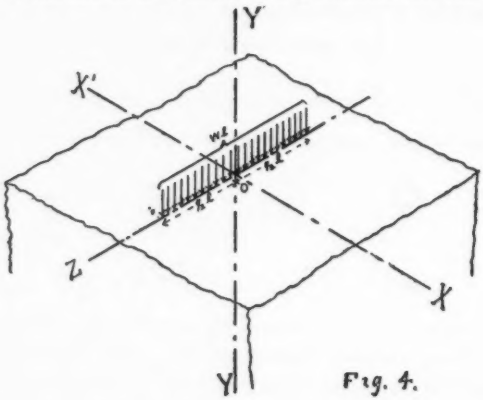


Fig. 4.

of $z' - \frac{1}{2}l$ and $z' + \frac{1}{2}l$. The resulting expressions are very complicated. If, however, the solution be limited to points close to the middle of the roller, and to values of x and y which are small in comparison with l, the formulas are much simplified, and become, after substituting for λ and μ in terms of E and σ,

$$\left.\begin{aligned}
u_p &= -\frac{W(1+\sigma)(1-2\sigma)}{\pi E}\cot.^{-1}\frac{y}{x} + \frac{W(1+\sigma)}{\pi E}\frac{xy}{h^2},\\
v_p &= +\frac{W(1+\sigma)(1-\sigma)}{\pi E}\log.\frac{l^2}{h^2} + \frac{W(1+\sigma)}{\pi E}\frac{y^2}{h^2},\\
w_p &= 0,\\
P_p &= -\frac{2W}{\pi}\frac{x^2 y}{h^4},\\
Q_p &= -\frac{2W}{\pi}\frac{y^3}{h^4},\\
R_p &= -\frac{2W\sigma}{\pi}\frac{y}{h^2},\\
S_p &= 0,\\
T_p &= 0,\\
U_p &= -\frac{2W}{\pi}\frac{xy^2}{h^4},
\end{aligned}\right\} \quad \ldots.(5)$$

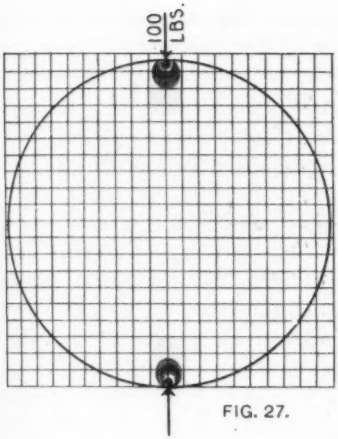


FIG. 27.

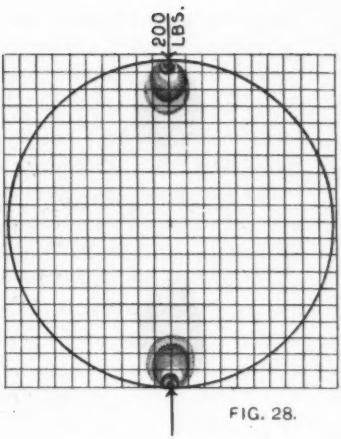


FIG. 28.

PLATE IV

INTENSITY OF STRESS BY POLARIZED LIGHT.

1.98" ROLLER, 1" LONG.

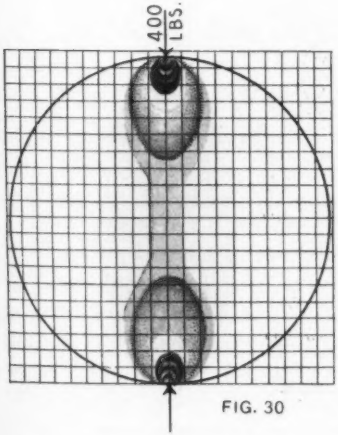


FIG. 30

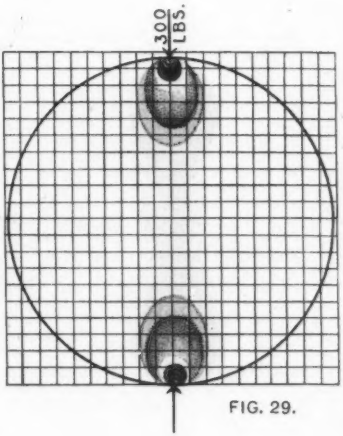


FIG. 29.

where h = the perpendicular distance from the point x, y, z, to the axis of z, and the logarithms are Napierian logarithms. It may readily be verified that the displacements above satisfy the fundamental equations (3), and that the stresses satisfy the boundary conditions.

The solution in (5) applies strictly, as has been said, only to the case where the bearing plate rests on a pier of the same material as itself. Practically, however, it does not seem probable that the nature of the material on which the bearing plate would actually rest will appreciably affect the stresses in it. Again, although the solution is strictly correct only for points in the plate near the middle of the roller, where x and y are small in comparison with l, yet, if the roller extends to the edge of the plate, they may be considered as a section of a roller and plate of infinite length, for which the solution would be true at all points of the plate. The only difference is that the roller and plate in the actual case are free to expand parallel to the axis of the roller, which will modify the value of R_p, but probably not greatly affect the other stresses.

On the whole, therefore, it may be said with some confidence that

$$\left.\begin{aligned} P_p &= -\frac{2W}{\pi}\,\frac{x^2y}{h^4}, \\ Q_p &= -\frac{2W}{\pi}\,\frac{y^3}{h^4}, \\ U_p &= -\frac{2W}{\pi}\,\frac{xy^2}{h^4}, \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

are the stresses in a bearing plate under the end of a bridge due a roller as long as the plate is wide, loaded with a weight W per unit of length.

In (6) the axis of Z is the line of contact between the roller and the plate, and the axis of Y is taken vertical. h = the perpendicular distance from the point (x, y, z) to the axis of Z. The stress on planes perpendicular to the axis of the roller is left out of account, it being assumed that it is normal to the planes. The equations do not hold true for points very close to the line of contact for the reason that there will, in reality, be a surface instead of a line of contact.

It will be seen that equations (6) are very simple in form. They can be still further simplified as follows :

Let N_p' and N_p'' be the principal stresses at any point of the plate, and let Θ_p be the angle which the line of stress at the point makes

with the vertical. Then, from Rankine's "Civil Engineering," pages 169 and 170—

$$\left.\begin{aligned} N_p' &= \frac{Q_p + P_p}{2} + \sqrt{\frac{(Q_p - P_p)^2}{4} + U_p^2}, \\ N_p'' &= \frac{Q_p + P_p}{2} - \sqrt{\frac{(Q_p - P_p)^2}{4} + U_p^2}, \\ \Theta_p &= \tfrac{1}{2} \tan.^{-1} \frac{2\,U_p}{Q_p - P_p} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (7)$$

From (7) and (6),

$$\left.\begin{aligned} N_p' &= O, \\ N_p'' &= -\frac{2\,W}{\pi}\frac{y}{h^2}, \\ \Theta_p &= \tan.^{-1}\frac{x}{y}, \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

From (8) it is seen at once that the lines of stress in a bearing plate, pressed as for (6) are straight lines perpendicular to the line of contact between roller and plate, and radiating from it, and that the stress is a simple compression, directed towards the line of contact, and of amount—

$$N_p = -\frac{2\,W}{\pi}\frac{\cos.\,\Theta}{h}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where Θ is the angle which any line of stress makes with the vertical, and h and W are as for (6). The axes of co-ordinates are taken as for (6), and the formula is subject to the same limitations. It will be more nearly correct at the middle of the plate than elsewhere.

(9) is very interesting as showing the law by which a uniform load applied to an elastic solid along a surface line distributes itself into the body of the solid.

To obtain a solution for the stresses in the roller itself, conceive the roller to be inscribed in a plate of thickness $2\,r$ (where r = the radius of the roller), and of width equal to the length of the roller, as in Fig. 5.

It is evident that (5) gives the stresses in such a plate, for, 1st, the load W per unit of length along the upper line of contact of the roller; 2d, to the distribution of stress over the lower face of the plate found by substituting $2\,r$ in the values of Q_p and U_p given in (5); 3d, to a distribution of stress over each side edge of the plate equal to the R_p of (5).

These stresses in the plate may be transformed to axes of co-ordin-

ates through the center of the roller as in Fig. 5, by substituting $r - y$ for y in (5). From this it is evident that the system of stresses—

$$\left.\begin{aligned} P'' &= -\frac{2W}{\pi}\left[\frac{x^2(r-y)}{h_1^4} + \frac{x^2(r+y)}{h_2^4}\right], \\ Q'' &= -\frac{2W}{\pi}\left[\frac{(r-y)^3}{h_1^4} + \frac{(r+y)^3}{h_2^4}\right], \\ R'' &= -\frac{2W\sigma}{\pi}\left[\frac{(r-y)}{h_1^2} + \frac{(r+y)}{h_2^2}\right], \\ S'' &= 0, \\ T'' &= 0, \\ U'' &= +\frac{2W}{\pi}\left[\frac{x(r-y)^2}{h_1^4} - \frac{x(r+y)^2}{h_2^4}\right] \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots(10)$$

[where h_1 and h_2 are the respective perpendicular distances from the point (x, y, z) to the upper and lower lines of contact of the roller] gives the stresses in the plate of Fig. 5, due, 1st, to the loads W per unit of length along each line of contact of the roller as in Fig. 5; 2d, to a distribution of stress over each face equal to the Q_p, and U_p of (5) when $2r$ is substituted for y; 3d, to the distribution of stress R'' over each side edge of the plate.

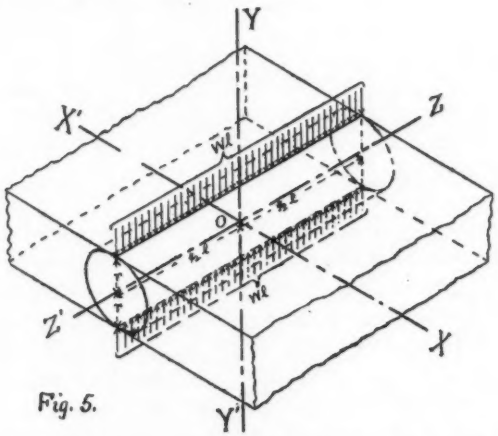


Fig. 5.

Or, they are the stresses in the roller shown in Fig. 5, due, 1st, to the load W per unit of length along each line of contact of the roller; 2d, to the reaction of the plate against the cylindrical surface of the roller; 3d, to the distribution of stress R'' over each end of the roller.

The reaction of the plate against the cylindrical surface may be computed by substituting $x^2+y^2=r^2$ in the expressions for P'', Q'' and T'' in (10). The results are $P''_s=-\frac{W}{\pi r}$, $Q''_s=-\frac{W}{\pi r}$, and $T''_s=0$.

Thus the stresses caused by the reaction of the plate against the roller may be nullified by adding to the P'' and Q'' of (10) the uniform tensile stresses $P'''=\frac{+W}{\pi r}$, and $Q'''=+\frac{W}{\pi r}$.

The double integral of R'' over the end of the roller $=-4\ W\sigma r$. It is well known that any two equal and opposite forces, parallel to the axis, applied symmetrically, one at each end of a cylinder, cause a simple uniform stress at all points in the cylinder except those very close to the ends, equal in amount to the quotient of one of the forces divided by the area of a right section of the cylinder. Hence the stresses due to the distribution of stress R'' over each end of the roller may be nullified by adding to the R'' of (10) the uniform tensile stress $+\frac{4\ W\sigma r}{\pi r^2}=+\frac{4\ W\sigma}{\pi r}$.

Making these corrections to (10), and calculating the corresponding displacements, the complete solution for the stresses and displacements in a roller of radius r, pressed above and below by loads W per unit of length is as follows :

$$
\left.\begin{aligned}
u_r &= -\frac{W(1+\sigma)\,(1-2\sigma)}{\pi E}\left[\cot.^{-1}\frac{(r-y)}{x}+\cot.^{-1}\frac{(r+y)}{x}\right] \\
&\quad +\frac{W(1+\sigma)}{\pi E}\left[\frac{x\,(r-y)}{h_1^{\,2}}+\frac{x\,(r+y)}{h_2^{\,2}}\right]+\frac{W(1-\sigma-4\sigma^2)}{\pi E}\frac{x}{r}, \\
v_r &= +\frac{W(1+\sigma)\,(1-\sigma)}{\pi E}\log.\frac{h_1^2}{h_2^2}-\frac{W(1+\sigma)}{\pi E} \\
&\quad \left[\frac{(r-y)^2}{h_1^{\,2}}-\frac{(r+y)^2}{h_2^{\,2}}\right]+\frac{W(1-\sigma-4\sigma^2)}{\pi E}\frac{y}{r}, \\
w_r &= +\frac{2\ W\sigma}{\pi E}\frac{z}{r}, \\
P_r &= -\frac{2\ W}{\pi}\left[\frac{x^2\,(r-y)}{h^4_1}+\frac{x^2\,(r+y)}{h^4_2}\right]+\frac{W}{\pi r}, \\
Q_r &= -\frac{2\ W}{\pi}\left[\frac{(r-y)^3}{h_1^4}+\frac{(r+y)^3}{h^4_2}\right]+\frac{W}{\pi r}, \\
R_r &= -\frac{2\,W\sigma}{\pi}\left[\frac{(r-y)}{h^2_1}+\frac{(r+y)}{h^2_2}\right]+\frac{4\ W\sigma}{\pi r}, \\
S_r &= 0, \\
T_r &= 0, \\
U_r &= +\frac{2\ W}{\pi}\left[\frac{x\,(r-y)^2}{h^4_1}-\frac{x\,(r+y)^2}{h^4_2}\right].
\end{aligned}\right\}\quad\ldots(11)
$$

In (11) the axes of co-ordinates are taken as in Fig. 5, h_1 = the perpendicular distance from the point (x, y, z) to the upper line of contact, and h_2 = the corresponding distance to the lower line of contact. The logarithms are Napierian logarithms. It may readily be verified that (11) satisfies (2), and (3), and the boundary conditions. The solutions do not hold true except at points sensibly distant from the areas of contact for the reason already given in connection with the bearing plate.

TABLE No. 2.

THEORETICAL STRESSES IN A ROLLER 1 IN. IN DIAMETER DUE TO A LOAD W PER LINEAL INCH OF ROLLER.

x	y	P_r	Q_r	U_r	N'_r	N''_r	$N'_r - N''_r$
0.0"	0.0"	+ 0.637 W	— 1.910 W	0	+ 0.637 W	— 1.910 W	2.546 W
0.0"	+ 0.1"	+ 0.637 W	— 2.016 W	0	+ 0.637 W	— 2.016 W	2.653 W
0.0"	+ 0.2"	+ 0.637 W	— 2.395 W	0	+ 0 637 W	— 2.395 W	3.031 W
0.0"	+ 0.3"	+ 0.637 W	— 3.342 W	0	+ 0 637 W	— 3 342 W	3.978 W
0.0"	+ 0.4"	+ 0.637 W	— 6.437 W	0	+ 0.637 W	— 6 437 W	7.073 W
— 0.1"	0.0"	+ 0.542 W	— 1.717 W	0	+ 0.542 W	— 1.717 W	2.260 W
— 0.1"	+ 0.1"	+ 0.521 W	— 1.777 W	— 0.185 W	+ 0.535 W	— 1.792 W	2.327 W
— 0.1"	+ 0.2"	+ 0.428 W	— 1.955 W	— 0.448 W	+ 0.509 W	— 2.037 W	2.546 W
— 0 1"	+ 0.3"	+ 0.115 W	— 2.172 W	— 0.922 W	+ 0.441 W	— 2.497 W	2.938 W
— 0.1"	+ 0.4"	— 0.964 W	— 1.645 W	— 1.515 W	+ 0.248 W	— 2.857 W	3.105 W
— 0.2"	0 0"	+ 0.334 W	— 1.255 W	0	+ 0.334 W	— 1.255 W	1.589 W
— 0.2"	+ 0.1"	+ 0.286 W	— 1.241 W	— 0.223 W	+ 0.319 W	— 1.274 W	1.592 W
— 0.2"	+ 0.2"	+ 0.121 W	— 1.157 W	— 0.456 W	+ 0.267 W	— 1.303 W	1.571 W
— 0.2"	+ 0.3"	— 0.203 W	— 0.864 W	— 0.619 W	+ 0.168 W	— 1.235 W	1.404 W
— 0.2"	+ 0.4"	— 0.414 W	— 0.260 W	— 0.366 W	+ 0.037 W	— 0.711 W	0.749 W
— 0.3"	0.0"	+ 0.141 W	— 0.740 W	0	+ 0.141 W	— 0.740 W	0.881 W
— 0.3"	+ 0.1"	+ 0.100 W	— 0.694 W	— 0 149 W	+ 0.127 W	— 0.721 W	0 849 W
— 0.3"	+ 0.2"	— 0.013 W	— 0.543 W	— 0.252 W	+ 0.088 W	— 0.644 W	0.732 W
— 0.3"	+ 0.3"	— 0.127 W	— 0.276 W	— 0.223 W	+ 0.032 W	— 0.436 W	0.469 W
— 0.3"	+ 0.4"	0	0	0	0	0	0

The stresses given in (11) may now be checked by comparison with the polarized light experiments. Let N'_r be the principal stress at any point at right angles to the line of stress passing through the point, and let N''_r be the principal stress in the direction of the line of stress. When P_r, Q_r and U_r are calculated by (11), N'_r and N''_r may be calculated by equations similar to (7).

The results in the 1-in. roller are given in Table No. 2.

For the 1.98-in. roller the results are given in Table No. 3.

By comparing the values of $N'_r - N''_r$ with Table No. 1, it may readily be ascertained what the colors should be at the different points of the figures in Plates XVI and XVII, to check with equa-

tions (11). On the original drawings, in the writer's possession, the theoretical colors are everywhere the same as the actual.

TABLE No. 3.

THEORETICAL STRESSES IN A ROLLER 1.98 INS. IN DIAMETER DUE TO A LOAD W PER LINEAL INCH OF ROLLER.

x	y	P_r	Q_r	U_r	N'_r	N''_r	$N'_r - N''_r$
0.0"	0.0"	+ 0.321 W	− 0.964 W	0	+ 0.321 W	− 0.964 W	1.286 W
0.0"	+ 0.2"	+ 0.321 W	− 1.019 W	0	+ 0.321 W	− 1.019 W	1.341 W
0.0"	+ 0.4"	+ 0.321 W	− 1.215 W	0	+ 0.321 W	− 1.215 W	1.537 W
0.0"	+ 0.6"	+ 0.321 W	− 1.711 W	0	+ 0.321 W	− 1.711 W	2.033 W
0.0"	+ 0.8"	+ 0.321 W	− 3.384 W	0	+ 0.321 W	− 3.384 W	3.706 W
0.0"	+ 0.9"	+ 0.321 W	− 7.088 W	0	+ 0.321 W	− 7.088 W	7.410 W
− 0.1"	+ 0.8"	− 0.249 W	− 2.087 W	− 1.062 W	+ 0.236 W	− 2.572 W	2.808 W
− 0.1"	+ 0.9"	− 1.428 W	− 1.430 W	− 1.556 W	+ 0.127 W	− 2.985 W	3.112 W
− 0.2"	0.0"	+ 0.273 W	− 0.866 W	0	+ 0.273 W	− 0.866 W	1.139 W
− 0.2"	+ 0.2"	+ 0.262 W	− 0.896 W	− 0.095 W	+ 0.269 W	− 0.904 W	1.173 W
− 0.2"	+ 0.4"	+ 0.213 W	− 0.986 W	− 0.231 W	+ 0.256 W	− 1.029 W	1.285 W
− 0.2"	+ 0.6"	+ 0.046 W	− 1.090 W	− 0.475 W	+ 0.219 W	− 1.262 W	1.481 W
− 0.2"	+ 0.8"	− 0.518 W	− 0.778 W	− 0.755 W	+ 0.118 W	− 1.415 W	1.533 W
− 0.2"	+ 0.9"	− 0.673 W	− 0.208 W	− 0.411 W	+ 0.031 W	− 0.913 W	0.944 W
− 0.3"	+ 0.8"	− 0.372 W	− 0.290 W	− 0.377 W	+ 0.048 W	− 0.710 W	0.759 W
− 0.4"	0.0"	+ 0.166 W	− 0.629 W	0	+ 0.166 W	− 0.629 W	0.794 W
− 0.4"	+ 0.2"	+ 0.142 W	− 0.621 W	− 0.113 W	+ 0.158 W	− 0.637 W	0.796 W
− 0.4"	+ 0.4"	+ 0.056 W	− 0.576 W	− 0.231 W	+ 0.132 W	− 0.651 W	0.783 W
− 0.4"	+ 0.6"	− 0.109 W	− 0.420 W	− 0.308 W	+ 0.081 W	− 0.610 W	0.691 W
− 0.4"	+ 0.8"	− 0.198 W	− 0.115 W	− 0.167 W	+ 0.016 W	− 0.328 W	0.345 W

By an equation similar to the third equation of (7), the angles made with the vertical by the lines of stress at the different points of the rollers may be computed from the values of P_r, Q_r and U_r in Tables Nos. 2 and 3. On the supposition that the lines of stress are arcs of circles, these angles would be given by the equation, cot. $\Theta = \dfrac{y^2 - x^2 - r^2}{2xy}$ which is derived in the same way as equation (1). The angles have been computed by each of these methods for a large number of points in each roller, and the results are identical. This shows that the lines of stress are arcs of circles, as was suspected from the results of the polarized light experiments. It should be possible to prove this algebraically from equations (11), but the writer has not succeeded in doing so.

That the distribution of stress in a bridge roller is of the general character shown by Plates XVI and XVII and equations (11) was confirmed in an interesting way by some experiments made at Cornell University in 1893 by Prof. C. L. Crandall and the writer. In the 300 000 lbs. testing machine of Sibley College, rollers of tool steel, 1 in. long and respectively 1 in. and 2 ins. in diameter, were pressed be-

tween bars of the same metal, 1 in. wide by ½ in. thick, as shown in Fig. 6. The sides of the bars were polished, and light was reflected on them from a mirror. As the elastic limit was passed, a line bounding the permanently distorted area made its appearance on each bar. The general shape of these lines, as well as the manner in which they shifted as the load increased, is shown by the dotted lines on Fig. 6. Allowing for the widening of the surface of contact between the roller and plate when the elastic limit was passed, due to the permanent indentation, it will be seen that these lines are of the same general shape as the color bands of Plates XVI and XVII.

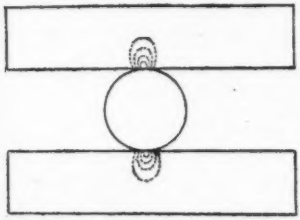


Fig. 6.

Under very great pressure the ends of the bars in the above experiments bent away from the surfaces on which they rested, and lines similar to those above described extended from the farther surface of each bar to meet the first lines.

The effect of the high loads put on these rollers was greatly to flatten them out, and to cause them to indent deeply into the bars. Finally, under a load of 168 000 lbs., the 1-in. roller began to shear through the bar.

It now remains to utilize the results of the preceding discussion in the derivation of a practical formula for the safe loads on bridge rollers.

There have been three practical formulas proposed, viz.:

$$W_s = C' \sqrt{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

which is the formula generally used in bridge specifications in this country;

$$W_s = \tfrac{1}{3} \sqrt{2\, w_s^3\, r \left(\frac{r}{E_r} + \frac{r'}{E_p} \right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

which is originally due to Grashof, but has been modified by Profs. Burr, Johnson and Eddy;*

and

$$W_s = Cd \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

which is the formula commonly used in Germany.

In the above formulas, W_s = the safe load per unit of length of roller, w_s = the safe stress in the roller or plate, r' = the thickness of

* See Burr's "Stresses in Bridge and Roof Trusses," pages 443-46.

the plate, r = the radius, and d = the diameter of the roller, E_r and E_p are the moduli of elasticity of the roller and plate respectively, and C' and C are empirical constants.

For equation (12) there is a theoretical derivation based on the assumption that the safe load will cause a certain fixed indentation of the plate for all diameters of rollers. Recently, also, Prof. Johnson has supported it on the ground that it is confirmed by the results of Profs. Crandall's and Wing's experiments with rollers 1 in. to 4 in. in diameter.*

The writer finds, however, that the results of these experiments will agree almost equally well with several different assumed formulas, and, in fact, they do not include a sufficient range of diameters to eliminate the effect of the irregularities of the tests. The results of these experiments are platted on Plate XVII.

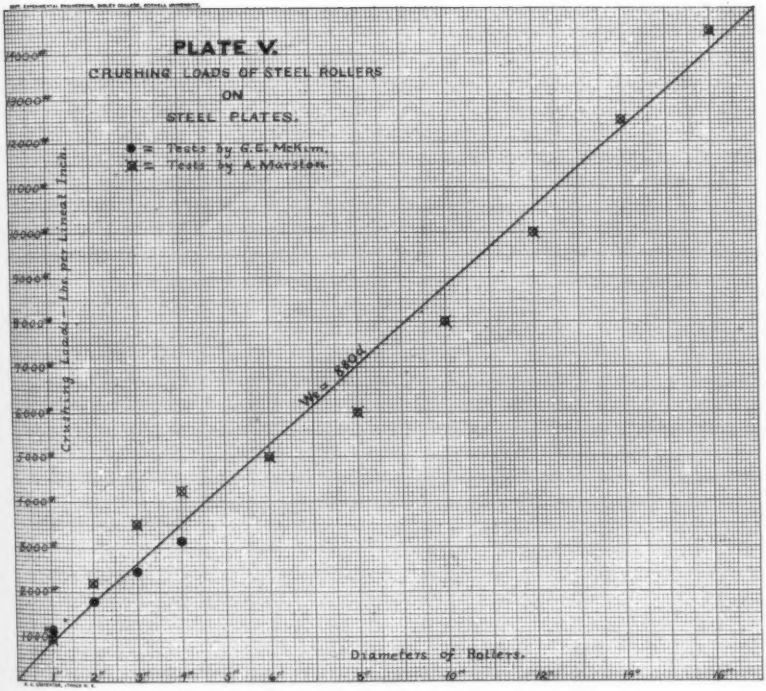
Equation (13) is based on the supposition that the whole of the stress in the roller is borne by the strip included between the verticals through the edges of the area of contact. A glance at Plates XVI and XVII, or at Tables Nos. 2 and 3, will show that this assumption is very far from the truth. Moreover, this formula would make the crushing load depend upon the thickness of the plate. That this is incorrect was shown by experiments made in 1893 by Mr. G. E. McKim, at the Iowa State Agricultural College. He determined the crushing loads for 1-in., 2-in., 3-in. and 4-in. steel rollers, bearing on plates 2 ins. thick, cut from the same piece of steel as the rollers, and then had the plates planed down to successive thicknesses of 1½ ins., 1 in. and ½ in., repeating the test with each thickness. The results showed no appreciable variation of the crushing loads for different thicknesses of plates, although for the 1-in. roller equation (13) would make the crushing load nearly 67% larger for the 2-in. than for the ½-in. plate. Mr. McKim's results are given in Plate XVIII.

When, in equation (13), r' is assumed equal to r, the resulting equation is of the form given in (14). This is the form used for practical purposes in Germany, as already stated. It is evident, however, that the assumption that $r = r'$ could not be correctly made for any great range of diameters of rollers, and Prof. Johnson, in a discussion before this Society,† has shown that the derivation of (14) from the Grashof formula cannot be accepted.

* See "Framed Structures," pages 273–77.

† See *Transactions*, Vol. XXI, page 206.

PLATE XVIII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 723.
MARSTON ON FRICTION ROLLERS.



The results of the solutions given in this paper for the stresses in the roller and bearing plate may, however, be utilized to give a rational basis for formula (14), as follows:

The displacements and stresses in (5) and (11) are strictly correct for points near the middle of the roller (provided x and y for the plate are small in comparison with the length of the roller) for a uniform distribution of pressure, W per unit of length, along a *line* of contact. In the actual case, the force W is distributed over an *area*, instead of along a line of contact. From the theory of "local perturbations" (see Love's "Theory of Elasticity," page 259), it is evident that the displacements and stresses of (5) and (11) will still hold true for all points except those very close to the area of contact. It is also evident that the pressure between the plate and roller is a maximum at the middle of the area of contact, and is 0 at the edges of that area, so that the greater part of W is applied near the middle of the area of contact. Hence the equations (5) and (11) may be assumed approximately correct up to the edges of the area of contact.

Let the middle line of the area of contact be taken as the axis of Z, let the axis of X for the plate lie in the surface of the plate before it is strained, and let the axis of X for the roller be tangent at the origin to the roller before it is strained. Before the strain the surface of the plate will be the plane $y_p = 0$. After the strain it will be the surface $y_p = \frac{W}{\pi} c_p \log. \frac{l^2}{x^2}$ (see 5), where $c_p = \frac{(1+\sigma_p)(1-\sigma_p)}{E_p}$. For small values of x, the surface of the roller before strain will be $y_r = -\frac{x^2}{d}$, and after strain it will be $y_r = -\frac{x^2}{d} - \frac{W}{\pi} c_r \log. \frac{d^2}{x^2} + \frac{2W}{\pi} c_r$ (see 11), where $c_r = \frac{(1+\sigma_r)(1-\sigma_r)}{E_r}$. The edges of the area of contact will be where $\frac{dy}{dx}$ for the plate, equals $\frac{dy}{dx}$ for the roller; *i. e.*, where—

$$-\frac{2W}{\pi} c_p \frac{1}{x} = -\frac{2x}{d} + \frac{2W}{\pi} c_r \frac{1}{x}.$$

Hence, if x_a = the value of x at the edge of the area of contact, and A = the width of the area of contact,

$$x_a = \sqrt{\frac{c_r + c_p}{\pi} Wd},$$

and

$$A = 2\sqrt{\frac{c_r + c_p}{\pi} Wd}, = K\sqrt{Wd} \ldots\ldots\ldots (15)$$

where K is a constant.

Since equations (5) and (11) are only approximately true up to the edges of the area of contact, K may be considered to be an empirical constant to be determined by experiment. To ascertain how close K probably approximates to $2\sqrt{\frac{c_r + c_p}{\pi}}$, the writer has computed A on the supposition that the distribution of the pressures over the area of contact is such that they can be represented by the ordinates to a parabola, as is assumed in the derivation of the Grashof formula. The result was that K for this case $= \sqrt{\frac{3}{2}} \times 2\sqrt{\frac{c_r + c_p}{\pi}}$, and the formula was still of the form (15).

The writer has compared formula (15) both with the measurements of the area of contact taken by Professors Crandall and Wing, and also with the results of a similar series taken by Mr. G. E. McKim, under the direction of the writer. Mr. McKim used three independent methods: First, by placing a sheet of impression paper between the plate and the roller; second, by injecting coralline dissolved in ether around the roller after the load was applied; and, third, by placing a coating of tallow on the plate before the load was applied. The results are given in Table No. 4.

TABLE No. 4.

SHOWING MEASUREMENTS OF AREAS OF CONTACT BETWEEN ROLLERS AND PLATES.

	Load on Roller 1½ ins. long.	Area of Contact.		
		By impression paper.	By ether and coralline.	By tallow.
	Lbs.	Ins.	Ins.	Ins.
1-in. roller	500	.0238	.0370	.0257
	1 000	.0370	.0383	.0305
	1 500	.0435	.0397	.0340
2-in. roller	500	.0435	.0487	.0338
	1 000	.0516	.0501	.0372
	1 500	.0538	.0523	.0395
	2 000	.0550	.0545	.0433
	2 500	.0575	.0570	.0472
3-in. roller	500	.....	.0515	.0411
	1 000	.0494	.0532	.0429
	1 500	.0524	.0549	.0464
	2 000	.0545	.0563	.0493
	2 500	.0565	.0575	.0530
	3 000	.0587	.0587	.0556
	3 500	.0610	.0601	.0590
4-in. roller	500	.....	.0541	.0461
	1 000	.0547	.0554	.0490
	1 500	.0573	.0567	.0522
	2 000	.0592	.0580	.0555
	2 500	.0615	.0592	.0578
	3 000	.0640	.0607	.0605
	3 500	.0664	.0618	.0635
	4 000	.0685	.0632	.0660
	4 500	.0700	.0645	.0685

The measurements in the above table are each the averages of two measurements, one on the plate, and the other on the roller. Formula (15) with K equal to $2\sqrt{\frac{c_r + c}{\pi}p}$, gives in every case results very much smaller than the measurements in Table No. 4, or than those by Professors Crandall and Wing. The writer thinks that this should be the case. Taking Mr. McKim's results with tallow as an illustration, if formula (15) is correct and K is taken equal to $2\sqrt{\frac{c_r + c}{\pi}p}$, the thickness of the tallow films at the edges of the areas he measured would be only about .00015 in., this thickness being remarkably constant for the different measurements, although the areas were more than twice those given by (15). It is evident that the eye in attempting to locate the limits of so thin a film of semi-transparent material, gradually diminishing to 0 thickness at the edges of the area of contact, would be apt to choose a place where the film is of appreciable thickness, as the theory indicates was done. Indications were not wanting in Mr. McKim's experiments, as the writer watched them, that the true area of contact was very much smaller than the one measured.

Assuming equation (15) to be correct, a formula for the crushing load may be derived by placing the average load over the area of contact equal to the average stress at the elastic limit of the metal of the roller or the plate, whichever fails sooner.

In a case of compound stress like the one under consideration, however, the elastic limit stress will not be the one determined by observations with pieces of metal subjected to simple stress in the ordinary way, but a very much higher limit, as all measurements of the area of contact have shown (compare Table No. 4), though such measurements are known to give average pressures smaller than the true pressures. The reason for this raising of the elastic limit was clearly stated by Mr. J. B. Francis, in the discussion of the paper on "Cylindrical Wheels and Flat Topped Rails," in Vol. XXI of the *Transactions*.* It has been questioned whether the value of the elastic limit stress for rollers will not vary for different diameters of rollers. The writer finds, however, by experiments covering a greater range of diameters than any heretofore made of which he has been able to

* See, also, the discussion by Professor Johnson, page 273, of "Framed Structures."

find record, that the average stress per unit of the area of contact of bridge rollers at the elastic limit is constant.

Call this stress w_e. By equation (15) the average stress over the area of contact, A, is $\frac{W}{A} = \frac{\sqrt{W}}{K\sqrt{d}}$, which at the elastic limit becomes $\frac{\sqrt{W_e}}{K\sqrt{d}}$, where W_e is the crushing load per unit of length of roller. Putting this equal to w_e, the average stress in the metal at the area of contact for the elastic limit,

$$W_e = K^2 w_e^2 d = C d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where C is an empirical constant to be determined by experiment. If W_s be the safe load per unit of length of the roller,

$$W_s = \frac{1}{f} \times C d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where f is the factor of safety used.

Although the writer has made a close search in all the technical literature to which he has access, he has not succeeded in finding any data as to the bearing strength of bridge rollers as determined by actual experiment, other than those of the experiments of Professors Crandall and Wing. In these, as has already been said, the range of diameters was not sufficient to eliminate the irregularities of the tests. The same is true of the experiments by Mr. McKim, to which reference has already been made. The lack of experimental data relating to the subject has led the writer to undertake a series of experiments to determine the effect of the diameter of the roller on the crushing loads of bridge rollers, the results of which, together with those of Mr. McKim's experiments, are platted in Plate XVIII.

Mr. McKim's experiments were made with rollers 1, 2, 3 and 4 ins. in diameter and 1½ ins. long, all cut from a piece of round steel 4½ ins. in diameter, obtained from the Illinois Steel Company. The bearing plates were 4 ins. square, and of different thicknesses, as already described. The lower plate, on which the observations were made, rested on a block of limestone 6 ins. thick. A chemical analysis of the steel gave the following results: Silicon, trace; phosphorus, 0.089%; sulphur, 0.135%; manganese, 0.507%; carbon, 0.370 per cent. The modulus of elasticity of this material, as determined by a compression test on a piece 1 x 1 x 10 ins. between caliper points, was 28 900 000 lbs. per square inch. The elastic limit stress, and the tensile strength, as determined by a test of a piece ¾ in. square, were, respectively, 31 000 lbs.

per square inch and 50 000 lbs. per square inch. The reduction of area at the fractured section was 31%, and the elongation in 8 ins. was 21 per cent. The crushing loads per lineal inch of roller are platted in Plate XVIII.

The writer's experiments, which have just been completed, were made with rollers 1, 2, 3, 4, 6, 8, 10, 12, 14 and 16 ins. in diameter, and 1 in. long, all cut from one steel plate by the Clinton Bridge and Iron Works, of Clinton, Ia. The bearing plates were 6 ins. square x 0.9 in. thick, cut from the same plate as the rollers. A chemical analysis of the steel gave the following results: Silicon, phosphorus and sulphur, a trace of each; manganese, 0.61 %; carbon, 0.24 per cent. The modulus of elasticity, as determined by a compression test of a piece 0.607 x 0.618 in. x 8½ ins. between caliper points, was 27 300 000 lbs. per square inch. The elastic limit stress was 36 000 lbs. per square inch; the tensile strength, 58 000 lbs. per square inch; the elongation in 5 ins., 31%, and the reduction of area of the fractured section, 60%, a test piece, 0.607 x 0.618 in. being used. The rollers were polished and the plates surfaced. The tests were made on a 50 000-lb. Olsen testing machine, at the Iowa State Agricultural College.

The elastic limit load for rollers bearing on plates is hard to determine very definitely, because the first permanent indentation is not perceptible to the eye unless the plate is held to the light in a favorable position. In these experiments the load at the elastic limit was determined by applying loads increasing by small increments from a safe value, and making a careful examination of the plate and roller after each load was applied, until a permanent indentation could be detected on the plate. In no case could a permanent mark be detected on the roller as soon as on the plate, probably because the shape of the former is not so favorable for detecting very slight deformations as that of the latter.

The results of these experiments are platted on Plate XVIII, together with those obtained by Mr. McKim. While the results show irregularities, these are not greater than can be explained by unavoidable differences in the accuracy of finish of the rollers, or in the quality of the metal from different parts of the same plate. The writer considers that the results are as conclusive as those of any one set of experiments can be in favor of the formula $W_e = C\,d$. The average value of C for the writer's experiments is 880 lbs. per lineal inch of roller.

For comparison, the crushing loads per lineal inch of Professors Crandall's and Wing's experiments are platted on Plate XIX, omitting those for the 4-in. wrought-iron roller, which were uniformly smaller than those for the smaller diameters of rollers of the same kind of material, because this fact would indicate a poor finish or a poor quality of material in the roller. It will be seen that the results were very irregular. Part of these irregularities was probably due to the fact that comparatively large increments of load were used in the tests, and part to differences in the accuracy of finish, or in the quality of the metal of the plates and rollers. The average lines for the different metals are drawn on the plate, assuming formula (16) to be correct. A careful study of Plate XIX will show that the experiments conform to this theory as well as to any other. The value for C for wrought iron and steel is much larger than the one determined by the writer's experiments.

If the formula $W_s = \frac{1}{f} C\,d$ be accepted as correct, there are strong reasons for changing the ordinary accepted bridge specifications to conform to it, which have been stated by Mr. George S. Morison in a recent paper, read before the American Society of Mechanical Engineers. The rule that the safe loads vary as the square root of the diameter of the roller encourages the use of small rollers, making the rolling friction greater, and causing greater danger of the expansion bearings becoming immovable through imperfections of workmanship, or other causes. Probably every bridge engineer can recall instances of his own observation, where the expansion bearings of bridges have proved, on inspection, to be in this condition. The rule that the safe load varies as the diameter will, when taken in combination with the use of segmental rollers, make it possible to obtain an economical expansion bearing with rollers of large diameters, and thus help to avoid this defect. Moreover, this rule is not an untried one, but has been used abroad.

In assigning the proper value for the factor of safety to use in this formula, account should be taken, on the one hand, of the fact that the pressure is seldom equally distributed over the roller by the ordinary end shoe of a bridge, and, on the other hand, of the fact that an excessive pressure on the roller is not so fatal a defect as it would be in other members of the bridge. Mr. George S. Morison uses in his practice the formula

$$W_s = 250\,d \qquad (18)$$

PLATE XIX.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 723.
MARSTON ON FRICTION ROLLERS.

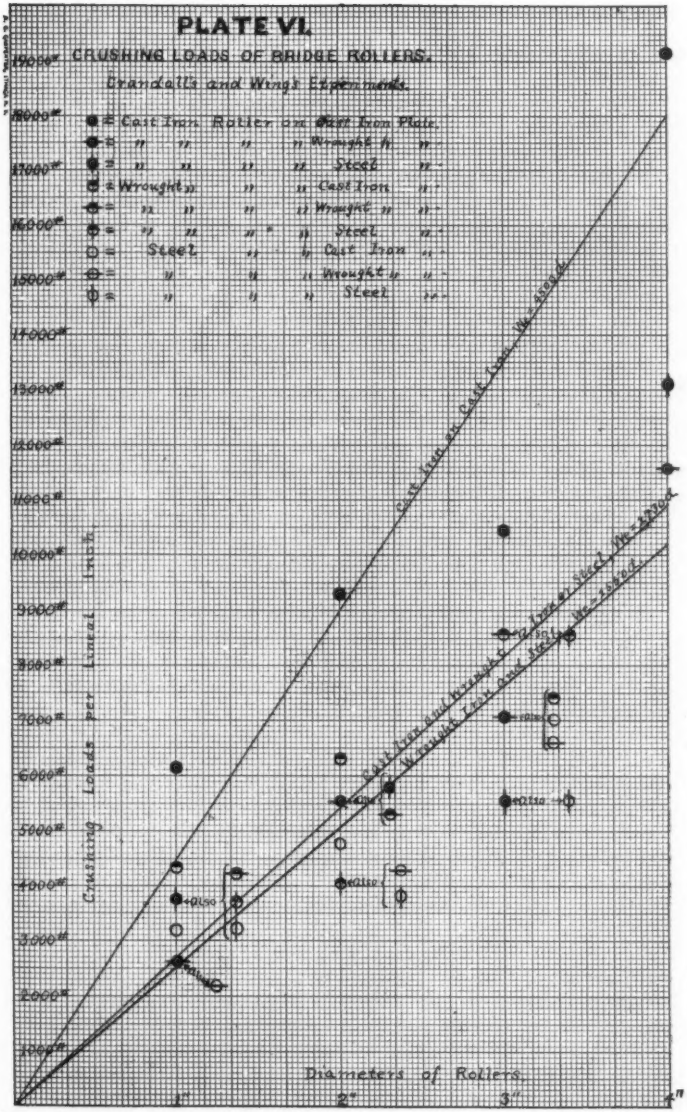


PLATE VI.
CRUSHING LOADS OF BRIDGE ROLLERS.
Crandall's and Wing's Experiments.
Cast Iron Roller on Cast Iron Plate.
" " " " Wrought " "
" " " " Steel " "
Wrought " " " Cast Iron " "
" " " " Wrought " "
" " " " Steel " "
Steel " " " Cast Iron " "
" " " " Wrought " "
" " " " Steel " "
Crushing Loads per Lineal Inch.
Diameters of Rollers.
1"
2"
3"
4"
Cast Iron on Cast Iron W=4000
Cast Iron and Wrought Iron on Steel W=4000
Wrought Iron and Steel W=4000

where W_s is the safe load in pounds per lineal inch of roller, and d is the diameter of the roller in inches. For a 4-in. roller this gives the same value for W_s as the ordinary formula $W_s = 500\sqrt{d}$.

For the writer's experiments, with rollers and plates of mild steel, formula (18) corresponds to a safety factor of 3½, which would certainly be sufficiently large; and the formula may be supported for all cases, on the ground that cast-iron or hard-steel rollers and bearing plates require a larger factor of safety than those of wrought iron or mild steel.

DISCUSSION.

W. R. HUTTON, M. Am. Soc. C. E. (by letter).—In addition to the observations upon glass under stress viewed by polarized light which are mentioned by Professor Marston, a very interesting series by Mr. A. Leger is illustrated and discussed in the memoirs of the Society of Civil Engineers of France for 1879. It has but slight bearing upon the particular form of stress under discussion here. Referring, however, to the double or triple iridescent ellipses at the point of maximum pressure, Mr. Leger observes that the glass scales off along the contours of these ellipses with undulated surfaces, and after rupture these surfaces are seen to be wavy and wrinkled (*ridé*) in conformity with the last polarized figures of the unbroken glass; and "jets" of striæ traverse these undulations in the direction of the "diffusion" of the interior forces; these waves mark the limit-deformation which precedes rupture.

I have not seen the paper in the *Physical Review*, as there is no copy of it in the library of our Society.

Besides the "practical" formulas for safe loads on bridge rollers on page 119, the following approximate rule, which I copy from Résal (*Ponts Métalliques*, page 92), for roller and plate of the same material, although it takes no note of the conjugate stresses, is based upon sound theory and is at the same time eminently practical.

Let d = diameter of roller.
a = half chord of indentation.
b = versed sine of same.
c = unit pressure on center line of contact (maximum unit pressure).
E = modulus of elasticity.

Assume, as is commonly done, that half the indentation is the compression of the roller at the point of contact;

$$c\frac{d}{2} = E\frac{b}{2} = \text{very nearly } E\frac{a^2}{2d};$$

The whole compression $= F = \frac{2}{3} c \times 2a$; combining and eliminating a,

$$F = \frac{16}{9} d^2 \frac{c^2}{E}$$

$$F = \frac{4}{3} dc \sqrt{\frac{c}{E}}$$

$$\frac{F}{d} = \frac{4}{3} c \sqrt{\frac{c}{E}}$$

The stress in the roller, therefore, varies directly as the diameter. The maximum unit pressure c of the roller on the plate must not exceed the elastic limit of the material. If, with Résal, we assume a factor of safety of one-half, we find for steel with an elastic limit of 30 000 pounds to the square inch, and $E = 27\,000\,000$, $F = \frac{4}{3} d\, 15\,000 \times \sqrt{\frac{15\,000}{27\,000\,000}} = 471d$ in pounds per lineal inch of roller. Mr. Morison's formula therefore is well within safe limits, and corresponds to a factor of safety of one-third, or a maximum pressure of one-third the elastic limit. These results also appear to coincide with Professor Marston's observations.

For cast iron, however, contrary to Professor Marston's conclusions, a much greater weight per linear inch of roller for the same diameter may be permitted.

C. L. Crandall, M. Am. Soc. C. E.—In connection with the remarks by Professor Marston, on page 126, in regard to the elastic limit of the rollers given on Plate XIX, it should be stated that the experiments were primarily for surface or contact rather than for elastic limit. Still, whenever either roller or plate was indented sufficiently to be apparent to the eye the fact was noted, as it was desired to keep within the elastic limit.

The following abstract of an article published in "Annales des Ponts et Chaussées," June, 1893, by M. H. Deslandres, describing some experiments upon the deformation of plates and rollers under compression, will be of interest in this connection as showing the amount of permanent set which takes place with small loads, and the point at which this set begins to increase much faster than the load.

Three rollers were used, each 200 mm. (7.87 ins.) long; the first, of cast steel, was 240 mm. (9.45 ins.) in diameter; the second, of cast iron, was 120 mm. (4.72 ins.) and the third, of cast iron, was 160 mm. (6.30 ins.) in diameter. The plates were all cast iron, 200 mm. (7.87 ins.) wide, and 80 mm. (3.15 ins.) thick.

Seven equidistant sections were marked upon the rollers and plates, and the compressed diameter at each section of the roller was compared with the diameter at an angle of 45° with it by a calliper scale

divided to hundredths of a millimeter (0.0004 in.), which was capable of being read with a maximum error of $\frac{2}{1000}$ mm. The indentation of the plate with reference to the surface on each side of the line of contact was measured at each of the seven corresponding sections by a plane-tester reading to the same fineness.

With the steel roller the permanent deformation is only given for a small range of loading, for which range it is constant and nearly zero.

For the plates compressed by the steel roller the permanent indentation begins with a load of 0.25 kgr. per square millimeter of diametrical section, = 356 lbs. per square inch, = 3 360 lbs. per lineal inch of roller, and increases directly with the load to 0.833 kgr. per square millimeter, = 1 185 lbs. per square inch, = 11 200 lbs. per lineal inch, for which the indentation = 0.45 cu. mm. = 0.0002 in. The next increment of 25% to the load increases the indentation over 120%, passing what the author calls the critical pressure.

For the small cast roller, the deformation is proportional to the load up to 1.042 kgr. per square millimeter, = 1 482 lbs. per square inch, = 7 000 lbs. per lineal inch of roller, for which the diameter is shortened 0.45 cu. mm. = 0.0002 in.

The next increment of 20% to the load adds 73% to the deformation.

For the large cast roller, the deformation is proportional to the load up to 0.443 kgr. per square millimeter, = 630 lbs. per square inch, = 3 970 lbs. per lineal inch, for which the diameter is shortened 0.30 cu. mm., = 0.0001 in. The next increment of 41% to the load adds 123% to the compression.

The author concludes that 0.44 kgr. per square millimeter is the theoretical limit for the cast rollers, giving a deformation not over $\frac{1}{3000}$ of the radius, while in practice he would limit the safe load to 0.22 kgr. = 313 lbs. per square inch of diametrical section.

For cast plates with steel rollers he places the limit $\frac{1}{2}$ less, or 0.18 kgr. = 256 lbs.

These values are slightly in excess of the 250 d of equation (18) used by Mr. George S. Morison.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

724.

(Vol. XXXII.—August, 1894.)

THE QUALITY OF WATER SUPPLIES.

By JOHN W. HILL, M. Am. Soc. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

WITH DISCUSSION.

The presentation to the Society of a paper on the self-purification of streams, by Dr. Charles G. Currier,* and one on fresh water algæ, by George W. Rafter,† M. Am. Soc. C. E., is the writer's apology for offering a paper on a subject, which, from its title, might seem better addressed to a health congress than to a society of engineers. But health boards and medical societies are usually powerless to rectify the evils to which attention is called by this paper. They may raise objections to existing conditions, and propose remedies, but to the engineer is finally entrusted the work of design and construction. Moreover, if the engineer engaged on a work of public water supply makes no mistake in selecting the source, or, the source being open to suspicion, he adopts the proper remedies to avoid injury to the consumers of water, then no question can be raised by health boards and medical associations. After all, it seems that health officers, physi-

* Trans. Am. Soc. C. E., Vol. XXIV, page 21.

† Trans. Am. Soc. C. E., Vol. XXI, page 493.

cians and analysts of water supplies can only demonstrate the evils, and aid the engineer in determining the cause, while the processes or devices for meeting or avoiding the danger are purely engineering problems, and as such should always be worthy of attention at our hands.

To members of the Society engaged in designing or operating works of public water supply, any inquiry into the quality of drinking water is usually always welcome, and, while the writer does not expect to offer any new facts, he hopes to be able to present some of the old ones in a way to carry conviction to doubting minds, of one of the principal dangers which now invests our sources of drinking water.

It is believed that water is a carrier of certain diseases, namely, cholera, typhoid fever and diarrhœa, and that the specific germ is transmitted from the sick to the well through the medium of drinking water.

It is also held by some investigators that the breaking up of vegetable detritus in drinking water may be the cause of disease, and it is well known that mineral poisons may be imbibed in drinking water.

Cholera is said, by Dr. Shakespere and others, to originate *de novo* in India, from the contamination of their drinking water by the filth of the native inhabitants,* and epidemics of typhoid fever and diarrhœa have been traced to wells,† or other sources of water supply, or to the ice used in cooling water,‡ the germs of disease being locked up in the ice and released upon its melting in the water.

Now, while water is held to be a carrier of disease germs, the writer is not aware that any investigator has ever claimed to have seen these germs in water, even under the highest powers of the microscope; and the evidence that water is such a carrier of pathogenic bacteria is obtained by inoculation from water samples, of nutrient media in test tubes, or on culture plates.

Thus, by methods quite indirect and open to grave errors of judgment in the hands of any but an expert, the fact of water carrying the spores of disease germs is established.

To those who have given the subject of bacteria no special study, it is proper to remark that the modern methods of bacteriology have

* "U. S. Rep. on Cholera in Europe." Dr. Edward O. Shakespere, 1890.

† "Bacteriological Study of Drinking Water." Dr. Victor C. Vaughan, Ann Arbor, Mich., 1892.

‡ "Water Supply." W. R. Nichols, 1883.

clearly proven that the soil, air and water swarm with bacterial life, and that countless micro-organisms and presumably organisms which cultivation and the microscope have not yet revealed, are steadily at work feeding upon and destroying the organic matter in these elements, and that we who drink water and inspire air are taking into the system thousands of these bacteria or their spores every day of our lives, from which it follows that first, all these bacteria are not pathogenic in character; or, second, the condition of the circulation or tissues of the human system are such as to repel their action and deprive them of a fertile soil, both of which are known to be true.

Of the so-called pathogenic bacteria, only a few have been proven to be the cause of disease, and of those which are known to accompany disease, although they may not cause it, they are said to be only active when brought in contact with a vitiated circulation, or with surface or internal lesions.

There can be no blood poisoning, excepting the germ of "septicæmia" be introduced into the circulation, and it can be introduced into the circulation only through a lesion of the skin or membrane.

So long as water contains organic matter in process of destruction, so long will bacteria be present in water, and some of these may be pathogenic bacteria, and lay the foundation for dangerous disease.

In considering the number of colonies of bacteria per unit of volume in a given water sample, it has been assumed that the number bears a just relation to the amount of organic matter in such water, and that any treatment of the water which diminishes the number of colonies of bacteria really does this by reducing the quantity of organic matter upon which such bacteria subsists. If all the bacteria, by any process, are removed from a sample of water, it is held that such water has been wholly deprived of organic matter, and, conversely, bacteria or other organisms harmless or harmful (to human life) cannot survive in a water wholly deprived of organic matter in a state of dissolution. It is possible that an absolutely pure water might be the carrier of a disease germ which accidentally came into it, but it is not likely that such germs could long subsist in a water deprived of pabulum for them, and they would soon perish for lack of subsistence, for bacteria, like any other vegetable growth, must have the proper nourishment, to sustain life.

The simple knowledge that organic matter exists in water, without

a knowledge of its source, is not worth much. Sugar is organic matter; so is excreta. Sugar in water would not be considered dangerous; excreta in water would be highly dangerous. Any organic matter in water will show an excess of ammonias above the normal, whether this be derived from safe organic compounds or from decomposing wastes; hence, a knowledge of the organic matter, independent of the knowledge of the kind of source of such matter, does not furnish reliable information upon the quality of a water sample. The chemical test for chlorine is usually relied upon to determine the probable source of organic matter, chlorine, usually from animal urine, indicating a sewage origin.

In classifying waters from high elevations, where the probabilities of sewage contamination are small, and waters from lowland sources, where the probabilities of sewage contamination are large, Prof. Frankland considers that the source or cause of pollution is more important than pollution itself, and proposes that waters from elevated sources may contain from one and one-half to twice the amount of organic elements (organic carbon and organic nitrogen) of lowland waters and still rank with the latter of any class (Frankland's "Analysis of Waters," page 94).

PARTS PER 100 000 OF ORGANIC ELEMENTS IN WATER.

Class.	Upland source.	Lowland source.
1. Water of great purity.....	0.2	0.1
2. Water of medium purity.....	0.2–0.4	0.1–0.2
3. Water of doubtful purity.....	0.4–0.6	0.2–0.4
4. Impure water.....	0.6 +	0.4—

The bodies of fresh water at lowest elevation of any geographical system are the rivers and lakes, and these are essentially the channels of discharge for the sewage of organized communities, as well as for that larger volume of decomposable wastes in the surface drainage from urban and agricultural territory; hence, organic matter in lowland waters, whether of rivers or lakes, is generally from sewage or semi-sewage sources, while organic matter in the waters gathered at high elevations is generally the result of vegetable detritus in the run-off of rainfall on unimproved or virgin water-sheds.

Chemistry enables us to determine as compounds containing nitrogen the organic matter in solution, while the microscope assists us in

the examination of the organic matters in suspension, but in doing so it has this advantage over chemistry, in that the examination is direct and not so much dependent on the personal equation as the results of chemical analysis.

A sample of rich sewage under microscopical observation will show micro-organisms capable of identification, together with masses of loose flocculent matter, which some term amorphous matter, but which the writer has indicated in his notes of tests as broken-up albuminous and cellulose matter. Such a sample, under continuous examination, will show a reduction of this loose matter, and in due time it will altogether disappear, the micro-organisms absorbing it, to support life; and with the disappearance of organic matter, there is a reduction of the vegetable and animal life in the water sample.

It is sometimes asserted that certain organisms are only found in good water, but the writer has observed, for instance, *Copepoda* in good cistern water, as well as in water known to be defiled by household wastes. If *Copepoda* alone were found in a water sample, the writer should not regard it as bad; but if associated with other and lower animal organisms and the lower kinds of filamentous algæ, he would consider such water as unsafe for drinking purposes. What is true of this particular organism, which is commonly found in soft waters, is true of any other organism supposed to inhabit pure water.

In order to approach the question of water pollution properly, it must be borne in mind that while polluted water is held to be the cause of certain diseases, exactly how it acts on the human system is not well known. Bacteriologists generally regard the Koch cholera bacillus, and the Eberth typhoid bacillus, as the causes of these diseases, but this view is not shared by all physicians as it should be if the proof of cause was sufficient, although common prudence should decide us in rejecting any water known to contain the cholera or typhoid bacilli, whether these germs be regarded as the cause or result of disease, since they indicate the presence of the cause if not the cause themselves.

The presence of putrefactive bacteria in a water sample is an evidence of decomposition going on in the water, but the disease, if any be derived from the use of such water, may not be due to the bacteria at all, but to some ptomaine obtained from the decomposition of the or-

ganic matter, or, as Professor Vaughan terms it, to some "toxicogenic" property of the water.*

While water may be a carrier of the cause of cholera, diarrhœa and typhoid fever, it is only the latter in which we are specially interested. Cholera may never arise *de novo* in this country, and diarrhœa traceable to a polluted water supply is seldom fatal, while typhoid fever is with us always, and, apparently, in all localities, and its ravages of the young, the bright, and the promising, are more to be dreaded than any of our infectious diseases, if we may except diphtheria, and, in the writer's opinion, it is more dreadful than diphtheria, because the latter is usually confined to the very young and undeveloped, while typhoid strikes down its victims as it were when they are on the very threshold of life; and, in discussing the danger of a polluted water supply, it will be from the single standpoint of its influence in the propagation of typhoid fever; although it may be well to remark, that, apart from the specific germs or sources of the diseases mentioned, water may contain common putrefactive bacteria which may not be hurtful in themselves, but which indicate the probability of the presence of organic matter in some of which there may be danger.†

The pumping of water for domestic uses from a source known to be polluted by sewage or otherwise cannot be too strongly condemned. The delivery of water containing the elements of fatal disease to a confiding and helpless community, partakes, in the writer's opinion, of the worst kind of criminality, and no one engaged in such work who is aware of this, or who refuses to apply the tests which will reveal the danger, if it exists, can hope to escape censure, even if, for lack of laws, he may escape a just punishment for his crime.

An attempt to kill people by the systematic distribution of a deadly poison would be met by the prompt arrest and punishment of the offender, but the delivery of a water for domestic uses as fatal to some as a dose of strychnine is permitted without a word of complaint. Why is this? Must we shut our eyes to the fact that polluted water is dangerous to health? Must we reject the results of the work of the patient investigators who have demonstrated over and over again that danger, often death, lurks in our drinking water? Or shall we recognize the peril and address ourselves to the task of rectifying an evil

* "A Bacteriological Study of Drinking Water," by Dr. V. C. Vaughan, 1892.

† Parkes' "Manual of Practical Hygiene," 1883.

greater than any other connected with the art of engineering? For the saving of human life, whether accomplished by medical remedies or the sanitary arts, is the noblest work to which man can set his hand.

The difficulty of procuring a satisfactory supply of potable water for large or even small communities, is well understood by the engineers engaged in this line of work. Sources of supply, which 10 or 15 years ago were thought to be safe in a sanitary aspect, are now open to grave suspicions of quality; and it is not extravagant to assert that few of the larger cities of the country enjoy a public source of water supply which satisfies the ordinary requirements of a potable water.

The increased sewage pollution of rivers and lakes which might furnish a safe drinking water is partly responsible for the difficulties surrounding this problem. But, apart from the special sewage pollution by organized communities, there is a pollution of streams and lakes by the ordinary surface drainage from agricultural water-sheds which often renders the waters of such unfit for drinking purposes.

Several years ago in discussing this question, the writer took the ground that, as the proportion of water used for drinking purposes was ½ per cent., or less, of the whole quantity consumed by the takers from a public source, the better plan was not to attempt to secure the whole supply of potable quality, but to render any water available fit for drinking purposes by domestic filtration. Later experience satisfies him that this plan will not answer for several reasons:

1. All consumers of a public water supply cannot, or will not, use domestic filters.

2. There is no domestic filter which is absolutely proof against the dangers of polluted water.*

3. Even if a satisfactory filter was obtainable, it is doubtful if the average householder would give this the attention it would require to keep it at all times in condition to act as a safeguard.

In view of which the writer has reached the conclusion that, if the consumer is to have a safe drinking water, it must come to him in this condition through the public water mains. In other words, the matter of purity must be looked after by the municipal corporation, or the water company. The prevalence of typhoid fever in many cities and

* Parkes, "Practical Hygiene," 1892.

towns having a public water supply is evidence of the water now generally furnished to consumers as being unpotable, and that the municipal corporations, or the water companies, are furnishing to their consumers the spores, or organized bacilli of the Eberth germ, or material from which the specific virus of typhoid is generated.

In speaking of the typhoid bacillus in water, it should be remarked that this has never been seen with the microscope without previous cultivation of the germ in nutrient media. Nor has it ever been demonstrated, so far as the writer is aware, that the presence of bacilli in water can be proven, excepting by delicate and difficult bacteriological processes.* It is well understood that the infective element of typhoid fever can be present in water and the chemical test be powerless to disclose it.†

In his excellent treatise on Sewage Disposal, Mr. Rafter aptly remarks "that absolute immunity from danger (by sewage pollution of water supplies) cannot be hoped for. There will always be some risk, even after the best has been done that is possible in any given case. And, so far as public water supplies are concerned, the true remedy lies in the direction of an absolutely uncontaminated source."‡

The only objection that can be raised to Mr. Rafter's method of securing an undefiled water supply is the great difficulty of its general application. For small communities requiring but a few hundred thousand gallons of water per diem, a supply of potable water can often be had from deep driven wells; but for large cities using many millions of gallons daily, such a source of supply is out of the question. It is doubtful if the water gathered on inhabited and improved water-sheds and impounded in large reservoirs for city supply, can be regarded as absolutely safe water for drinking purposes. Neither is it proper that lakes without current or circulation, and often the receivers of city sewage, should be considered as undefiled sources of supply.

Rivers receiving the sewage of cities and towns on their banks, and on the banks of their tributaries, certainly are not within the limitation of Mr. Rafter's sources, and where, then, are we to obtain the large volumes of water daily required by our larger cities, and have the same free from contamination at its source? Cities located in the moun-

* Sternberg, "Manual of Bacteriology," 1893.
† Frankland, "Water Analysis," 1890.
‡ Sewage Disposal, by Geo. W. Rafter and M. N. Baker, 1894.

tainous regions can impound water at elevations so high as to avoid pollution from all sources but the atmosphere, and this, as well as water, is always purer than in the valleys and on the lowlands. But for the larger cities of the middle States, having no mountain sources within practical reach, and without visible sources of supply which will satisfy Mr. Rafter's requirements, our only resource is to accept such water as is available in large quantities, and so deal with it as to render it innocuous to health.

It is too frequently asserted or implied in text books and reports on sewerage, that the noxious properties of sewage are destroyed or safely mitigated by proper dilution, but if sewage should be the carrier, as it undoubtedly often is, of pathogenic germs, how can dilution remove them? It may reduce the number per unit of volume of the mixed sewage and water, but the germs are still there, and when taken into the system through drinking water, may produce just as serious results to just as many people as if no dilution had occurred. Dilution may reduce the chances of any single individual imbibing a fatal germ, but the germ itself will be just as dangerous when it is imbibed. In speaking of germs in this connection, it must be understood that they are not limited to organized bacteria, but are meant to include any toxic property of water which may be derived from a sewage source.

The common opinion that the number of germs in a water sample is an index of its potability is apparently not well founded; for instance, from Dr. Victor C. Vaughan's extensive and able investigation of Michigan's waters, we note, that water from Torch Lake, Mich., containing 5 284 germs per cubic centimeter in a beef tea solution was fatal to rats, and well water from the same place, containing only 20 germs per cubic centimeter in a culture of beef tea, was also fatal to rats. Both of these waters were suspected of being the cause of typhoid fever. River water from Mount Pleasant, Mich., containing 3 000 germs per cubic centimeter in a culture of beef tea, had no effect on rats, while artesian water from Gladwyn, Mich., containing 10 germs per cubic centimeter in the same culture, was fatal to guinea pigs. Lake water from Soudan, Minn., containing 459 germs per cubic centimeter in the same culture, had no effect on rats, while well water, also from Soudan, containing four germs per cubic centimeter in the same culture, was fatal to rats.* Of course, Dr.

* "A Bacteriological Study of Drinking Water," by Dr. V. C. Vaughan.

Vaughan's tables contain illustrations the opposite of these, but these demonstrate clearly that the number of germs is not a safe index of the quality of the water sample (see Sternberg's "Manual of Bacteriology," page 558).

What is desired is not so much that the germs be reduced to a small number, as it is to eliminate altogether those of a pathogenic character. A man in jumping a brook must accomplish the feat in one leap. He cannot jump half way across and rest, and then jump the other half at his convenience. So it seems to me in dealing with the subject of water purification; we cannot partially purify it, and then deliver it to the consumers, without great risk. The bacteria, or other cause of disease, must be wholly eliminated, or we will be in the predicament of the man who attempts to cross the brook in two jumps, we will be worse off than if we had remained on the hither side; for a partial purification of our drinking water will beget a feeling of security which is false and may lead to serious results, while no attempt at purification at all will leave us on our guard against a polluted water, and cause us to avoid the drinking of it altogether.

In reports of filters tested for the reduction of bacteria it is customary to state the condition of the water in bacteria per cubic centimeter before and after filtration. These are given as the average per cubic centimeter and often the number after filtration may be as low as three or four, and the writer has seen it stated as low as one per cubic centimeter. An ordinary drinking tumbler contains half a pint, or about 230 cu. cm., and with the best of filtrated water so low in bacteria as one or two per cubic centimeter, a person may imbibe from 250 to 500 bacteria in drinking a single glass of water, some of which may be pathogenic and produce typhoid fever, or some other less dangerous disease.

Heretofore the writer has concurred in the popular belief that ordinary filtration of polluted water through some of the well-known modern filters would render it reasonably safe for drinking purposes, but from recent investigations of his own he is compelled to abandon this view. In the case of Cincinnati, with which he is familiar, the public water of which is notoriously unfit for drinking, nearly every public house and many business establishments are supplied with some form of sand filter or with the Pasteur filter, and yet Cincinnati takes high rank for its number of cases and deaths from typhoid fever.

Dr. Frederick Kebler, a skillful bacteriologist and eminent physician, informs the writer that even the celebrated Pasteur filter is not proof against the passage of bacteria; that these attach themselves to the outside of the porous porcelain tube, and, by growth and fission, eventually appear upon the inside of the tube, and may be found in the filtered water; and, from the writer's own examination of a section of a Pasteur filter tube under the microscope, he conceives that the pores are large enough to pass bodies of considerable magnitude, *i. e.*, from a microscopic standpoint.

Filtration through a Pasteur tube can accomplish no nitrification by bacterial agency, and poisons, or the base of ptomaines in solution, are certain to be found in the filtered water.

It is said by the manufacturers that the porosity of a Pasteur filter is equivalent to 1 micron (u), or $\frac{1}{25000}$ in. Now, the average diameter or thickness of a typhoid bacillus is $\frac{1}{2}$ micron (u),* and the spores very much less.† From which it appears that the Pasteur filter tube is open to the unrestricted passage of the germs and their spores, if such should have a habitat in the water.

There being no nitrification in passing through a Pasteur tube, no change can possibly be effected in the organic matter in solution in the water. For this, as we understand, can only be accomplished by boiling, chemical reactions, or by the nitrifying action of bacteria. In this respect a sand filter, properly constructed and worked, should yield a better filtrate than a Pasteur filter. But, as sand filters are usually worked, it is probable that they not only fail to remove organic matter in solution, but some of that in suspension may pass through, the only test of the filtrate being its limpidity, and it is well known that waters may be clear as crystal and still contain much organic matter in suspension, and all it ever had in solution. Clear water may be very dangerous water, as witness some of the spring waters sold in Boston and vicinity recently tested by Prof. T. M. Drown.‡

The so-called sanitary tests of water by chemists, when unsupported by careful microscopic tests, and this again fortified or checked by tube and plate cultures from the water sample in question, cannot be accepted as proof of quality, since "the existence of an

* Cruikshank, "Manual of Bacteriology," 1890.

† Rafter & Baker, "Sewage Disposal," 1894.

‡ Twenty-third Annual Report, Mass. State Board of Health.

infectious property in water cannot be proved by chemical analysis alone." *

The Pasteur filter acts simply as a very fine strainer, and is capable only of removing impurities in suspension in the water, impurities in solution being wholly unaffected by it. If the water upon which the filter acts is already chemically pure, and it is desired to remove organic matter in suspension, such as animal and vegetable organisms, clay silt, etc., then the filter can be relied upon to restrain these in passing through the tube. The popular idea, shared by many physicians, that the Pasteur filter is a safeguard against all manner of impurities in water is a fallacy. A sewage-polluted water may be as dangerous to health after it has been run through a Pasteur filter as it was before.

To satisfy himself upon this question, the writer has run through Pasteur filter tubes solutions of aniline purple, sulphate of quinine, sugar, starch, sulphate of copper and carmine, and has recovered in the filtrate all, or nearly all, of the original weight of the solid in solution. In making this test generally 1 gr. of the solid was dissolved in 200 cu. cm. of distilled water.

Of late years many Pasteur and sand filters have been installed in Cincinnati, and the general belief is established among the people that water from them is deprived of pathogenic properties, and yet the case and death rate from typhoid fever seems to be unaffected by their use. The writer thinks this is due to the fact that the spores or the bacilli of the typhoid germ (if such exist in water in a developed state), as well as any poisons in a solution, pass unchanged through the pores of the tube. The porosity of the Pasteur tube is probably much less than that of any sand filter in use in the city, and any matters not intercepted by a Pasteur tube would pass with less restriction through the bed of sand. The writer does not understand that any claim of nitrification is made for the common continuous sand filter, but that this, like the Pasteur, is expected to act simply as a very fine strainer.

Of course, it is unreasonable to suppose that all typhoid cases in Cincinnati can be traced to the use of water from Pasteur and other filters, but in some cases it can be so traced. A single case wherein filtered water alone was used as a beverage raises a just suspicion of the capacity of the filter to effectually restrain the typhoid bacillus or

* Frankland Water Analysis, 1880.

its spores from passing through the porcelain tube or bed of sand, or raises a doubt of the Eberth bacillus, or any other water bacteria, being the true cause of typhoid; and this suggests that the germ theory of disease, so ably expounded by Pasteur and Koch, is not universally accepted, many still holding to the Leibig theory, namely, "that disease is due to organic matter in process of decay communicating the elements of decomposition."

It is known that a Pasteur filter after it has been in use for some time may permit the passage of bacteria, and it will be necessary at frequent intervals to subject the tubes to a high temperature for the purpose of destroying all organic matter contained in the porous porcelain.*

Dr. Currier has shown that plate cultivations of bacteria can be made from water after it has passed through a Pasteur filter,† indicating that such water is not sterilized. It has been stated that the channels through the Pasteur tube are said by the makers in this country to be about $\frac{1}{25000}$ in., or 1 micron, in diameter, if considered as a round perforation. Now, many bacteria are less in diameter than a micron (Cruikshank), and the spores of all bacteria are much less in diameter than the developed organism. May it not be possible that the smaller bacteria or their spores pass unchanged through the porous Pasteur tube? The writer is aware that this theory is contrary to the common belief that water absolutely sterile and fit for bacteriological purposes is obtained by this mode of filtration, but the question is submitted for what it is worth. He feels safe, however, in asserting, from his own observation here in Cincinnati, that if absolutely sterile water is obtained from Pasteur filters, that the cause of typhoid fever cannot be found in the Eberth bacillus, but is due to a specific poison or ptomaine in the water, which the filter is powerless to remove.

From experiments by Drs. Frankland and Tidy‡ on the sewage of London and other English cities, the organic matter in solution will range from an equal amount to twice the quantity in suspension. Experiments by Mr. Dibden on London sewage show the ratio of dissolved to suspended matter to be as 1.00 to 0.77, or, of the organic matter in sewage, the larger part is in solution and wholly beyond the influence of any filter which acts simply as a strainer.

* Sternberg, "Manual of Bacteriology," 1893.
† Trans. Am. Soc. C. E., Vol. xxiv.
‡ Tidy, "Treatment of Sewage," 1887.

The only effective filtration is that in which the organic matter in solution, as well as the suspended matter, is removed from the water, and any filter failing to do this cannot be considered a success from a hygienic standpoint.

To determine the character of any water before and after filtration, or of any water about to be adopted for public uses, tests should be made chemically, for the ammonias, chlorines, nitrites and nitrates, for solids and hardness of water, and, if suspected, for mineral poisons, microscopically for the organisms and amorphous matter; and bacteriologically for the bacterial life in the sample of water. If the chemical test fails to develop any dangerous matter in solution, if the test with the microscope shows no low or objectionable organisms and no amorphous matter, and the test for bacteria reveals no pathogenic or parasitic microbes, such water, in the light of present knowledge, is possibly the best for drinking purposes we can hope for.

The city of Cincinnati has been well supplied for several years with mechanical filters, and yet, from statistics gathered by Dr. Stallard, of San Francisco, this city, of six in this country and five in England, stands at the head in mortality from typhoid fever, having a death rate four and a half times as great as that of London, higher than that of Philadelphia, and twice as great as Boston.

Admitting typhoid to be a water-borne disease, then it appears from its prevalence in this city (Cincinnati) that the filters in use here are worthless in combating the cause. In other words, the danger from typhoid seems to be as great after our water has been filtered as before.

The Ohio River, before it reaches Cincinnati, receives the sewage and surface drainage of upwards of 100 cities and towns, many of which have systems of sewers to facilitate the discharge of their sewage into the river or its tributaries. When the stream reaches Cincinnati the dilute sewage is pumped into the reservoirs and served to the people. What is true of the river at Cincinnati is emphasized as we proceed down stream, this city enriching the sewage-laden stream to the extent of 36 000 000 galls. per day, as a dry weather discharge, and, of course, many times that quantity during periods of rainfall, when our street wastes are washed into the sewer and carried into the river.

The water supplied to Cincinnati is not worse than that supplied to some other cities. But negligence or indifference in this respect by

our city does not justify it in any other, and if the same energy that is given to politics by the officials of Cincinnati was applied to the securing of a supply of pure water, there is no doubt that our water quality would be improved, and our alarming death rate from typhoid fever be diminished. Here, at least, and possibly in other cities, politics and water do not mix, and the harvest of our dearest idols goes on without restraint.

While it is not certainly established that typhoid cannot be acquired by other processes than water, milk or food, the weight of evidence now before us is that it is nearly always brought into the system through drinking water.

Considering typhoid as a water-carried disease, and assuming that one who drinks only pure water cannot contract it, then it follows that with pure water universally supplied to consumers, typhoid will no longer exist.

The Massachusetts State Board of Health has made extensive experiments on the filtration of water through beds of sand and loam, with very satisfactory results,* but at such slow rates of filtration (23 to 69 galls. per square foot of sand bed per day) as to discourage the adoption of this method in treating large volumes of water.

A report before the writer of a test of one of the mechanical sand filters shows about the same results in the removal of bacteria at rates of filtration as high as 166 000 000 galls. per acre per day, as the Lawrence experimental filters give at rates of 2 000 000 galls. per acre per day; or, while working at a rate of filtration over 80 times as great, the mechanical filter gives the same efficiency in removal of bacteria.

It is common for physicians in cases of doubt of the purity of a water supply to recommend that water for drinking purposes be boiled, but the boiling of water renders it insipid and unpalatable, and it is claimed by some of the manufacturers of filters that water deprived of certain of its natural gases and solids in solution (as it will be by boiling) is not as wholesome as natural waters. The writer has been unable to obtain any reliable information of the influence on the human system of the harmless salts and gases in solution in natural waters, and is in doubt whether the continuous use of boiled water as a beverage will be deleterious. Considering that filtered and boiled water will be limpid and sterile, and deprived of all toxic properties,

* Twenty-third Annual Report, Mass. State Board of Health.

and assuming that such water will not be injurious to the system, may not the problem of a safe drinking water finally be solved by combined filtration and distillation? If carried out to its legitimate conclusion, this would mean the treatment of a sufficient quantity of water by the corporation for drinking and culinary purposes, and the delivery of this to consumers through an independent system of comparatively small mains. But the expensive apparatus for distillation, the cost of duplicating the street mains, even with pipes of small diameter, and especially the large annual expense of operation, might at first sight seem to prohibit any attempt by this process to purify water on a large scale.

As this question is sometimes raised in the discussion of quality of water, it may be of advantage to inquire what will be the cost of procuring absolutely pure water by filtration and distillation combined.

Assuming a daily consumption of 1 000 000 galls. of potable water, or 347 100 lbs. per hour, an efficiency of 75% for the evaporating apparatus = 11 250 thermal units per pound of coal, and an average of 1 124 thermal units required per pound of water evaporated, then 1 lb. of coal will distill 10 lbs. of water at atmospheric pressure, and the consumption of coal will be 417 tons (2 000 lbs.) at $2 per ton, or $834 per day.

Estimating 3 lbs. of water evaporated per hour per square foot of heating surface, then to deal with 1 000 000 galls. per day there will be required 115 700 sq. ft. of heating surface, and, allowing 2 000 sq. ft. per boiler, will require 58 boilers. Tubular boilers, 7 ft. diameter, 18 ft. long, will cost, set and trimmed, $1 800 each, or $104 400 for the requisite number. Boiler house to accommodate them, $35 000. Allowing 10 lbs. of steam condensed per square foot of cooling surface in condensers, then 35 surface condensers, with 1 000 sq. ft. of cooling surface to each, at a cost of $52 500, will be required. Two sets of sand filters, each of 1 000 000 galls. daily capacity, will cost $12 000; filter house, $4 000; pipes, valves and sundries, about $20 000; total, $227,900, or in round numbers, $228 000.

ANNUAL EXPENSE.

Interest on cost at 5%	$11 400 00
Sinking Fund to redeem bonds in 40 years, at 4%.	2 398 56
Fuel, $834 × 365 days	304 410 00
Labor, 45 men at $2 per day, 3 men at $5 per day,	38 325 00
Total, not including repairs	$356 533 56

and the cost of so purifying water will be about $\frac{1}{10}$ of one cent per gallon.

In the items of cost no allowance is made for pumping, because this would be required in any case, whether the water is treated before delivery, or pumped without treatment from the source to the consumer; nor for cooling water for the surface condensers, because the 97 or 98% of untreated water may be made to pass through the condensers as cooling water without extra cost.

This, however, is not the whole cost, for allowance must be made for a duplicate set of mains of small diameter to distribute this water. Estimating 250 miles of mains at an average cost of $4 500 per mile = $1 125 000.

ANNUAL CHARGE.

Interest on cost at 5%	$56 250
Sinking Fund to redeem bonds in 40 years, at 4%	11 835
Total	$68 085

Cost per gallon of water treated, about $\frac{1}{10}$ of one cent, or a total cost of $\frac{12}{100}$ of one cent.

Thus, water absolutely free from all germs and their spores, and free from all toxic properties and matter in suspension, can be obtained, if the work of purification is conducted on a large scale, at the rate of 8 galls. for one cent.

Is absolute immunity from typhoid fever, cholera and all other water-borne diseases worth this expense? The writer thinks it is.

Applying this total annual cost to the city of Cincinnati, with a population of 325 000, then the annual cost for the prevention of typhoid fever in this city, will be about $1 31 per capita. Considering the fact that we had over 400 cases of typhoid in the city from December 12th, 1893, to January 12th, 1894,* it would seem that this annual amount per capita is not great for immunity from this disease. Whatever may be said in this paper with reference to Cincinnati will apply to any other city similarly cursed with a public water supply which may, sooner or later, carry disease and death into every household.

From a communication to the writer by one of the principal manu-

* This statement was made to the writer by one of our leading physicians.

facturers of sand filters in this country upon the method pursued in freeing water of bacteria and dissolved organic matters in the continuous sand filter, he takes the liberty of making the following extract:

"Our method of purifying water is both chemical and mechanical, and consists in first treating the water with a suitable reagent, so as to render the objectionable matters insoluble and coalescent. We then allow five minutes to one-half hour for the coagulation or conglomeration of the precipitated substances, and finally pass the water through a filter bed of white machine-crushed quartz, which much resembles in appearance and size granulated sugar. The filtering beds in our filters average about 2 ft. in depth, through which the treated water is made to pass or percolate. The grains of the filtering material are sharp and easily retain the coagulated substances, whatever they may be, upon and in the interstices of the bed, so that the water after passing through the filtering bed of quartz emerges clear and brilliant and free from whatever objectionable impurities were previously aimed to be removed.

"The proper treatment of the water prior to filtration is as important as filtration itself, for it is evident that a filtering bed composed as above described would be too free and open to arrest only the grossest matters in suspension. A bacterium or spore is, as you know, from $\frac{1}{20000}$ to $\frac{1}{100000}$ in. diameter; while probably the smallest of the interstices in the bed would not be less than $\frac{1}{100}$ in. in breadth. There are, therefore, but two mechanical methods available for retaining these germs. One, which is the method followed by the Pasteur, being to provide crevices or passages through the filtering material a trifle smaller or finer than the smallest bacterium. The other method is to coagulate the bacteria into masses large enough to be retained by larger passages. To effect this coagulation or conglomeration of the bacteria, sulphate of alumina or alum is used. The action of the sulphate of alumina is briefly as follows: When it is added to the water it decomposes the bicarbonates of lime and magnesia always present in waters to a more or less extent, and the products of the double decomposition are sulphate of lime or sulphate of magnesia, and carbonic acid gas and hydrate of alumina. The former two are as soluble as they were originally, and remain in the water; the latter is, however, insoluble, and is precipitated as a white, gelatinous mass, and, being coalescent in itself, envelopes the bacteria which adhere to it, and, therefore, when this precipitate of alumina is filtered out of the water, the bacteria, spores and all the infinitesimal matter in suspension is retained in the precipitate, and the water, therefore, can be easily and rapidly filtered through a filtering bed that would be absolutely worthless if no chemical treatment were used.

"Regarding the dissolved matters would say that these are removed by precipitating them directly, as, for instance, where lime and

magnesia are objectionable, we use sal soda or soda ash or caustic soda to precipitate the lime as carbonate, and this precipitate can be readily filtered out with our filter, therefore depriving the water of its lime and magnesia which was originally in solution, as it is in some of our sparkling artesian waters; as a result, the water is rendered perfectly or practically soft. The dissolved organic matters are almost entirely removed in the same manner by the alumina at the same time the bacteria are removed. We further remove the dissolved organic matters by subjecting the waters to aeration, which consists in forcing air into the water, oxidizing the decomposable organic matter which converts them into nitrites or nitrates, which are inert and harmless. These are the three methods most generally used in the purification of waters, although there are cases where special treatment is required. The average amount of alumina used does not exceed one-fourth of a grain per gallon, which is but 32.55 lbs. per 1 000 000 galls., and costs about $1\frac{5}{8}$ cents per pound."

Apart from a bed of sand common to all such filters and which acts only as a strainer or intercepter of suspended matter, the purification of water by the continuous sand filter appears to depend upon—

First.—The use of alum as a coagulent, to act upon the bacteria and dissolved salts in solution.

Second.—The use of soda ash or other reagent for softening purposes.

Third.—Aeration to oxidize dissolved organic matter and convert these into nitrites and nitrates.

Regarding the use of alum in sand filters much diversity of opinion exists. The manufacturers of these filters recommend it because it produces a clear filtrate while working the filter at a high rate of delivery, but in such uses of the mechanical sand filter as have come under his control, the writer has discouraged the corporations or water companies in the use of alum or any other astringent for precipitating the suspended organic matters, fearing that the excessive use of the coagulent would result in injury to the animal system. He is informed, however, by several of the manufacturers of mechanical sand filters that no harm can result from a surplus of alum, because any excess above that required to precipitate matters in suspension will unite with the mineral bases in solution in the water and produce insoluble or harmless compounds, as sulphate of lime, sulphate of sodium and hydrated alum. Upon the other hand, the excessive use of alum in a sand filter in one of our Cincinnati hotels, several years ago, was believed at the time to have produced among the regular boarders serious

bowel troubles, which were said by physicians in attendance to be due to the action of the astringent in the drinking water on the absorbent vessels of the stomach and intestinal canal. At best, the alum probably acts only on matters in suspension in the water, and has no influence on matters in solution * if these are derived from sewage sources.

The use of sal soda, soda ash or any reagent for softening the water would be demanded from a strictly sanitary standpoint only with those waters of great hardness, since small quantities of lime and magnesia are not generally regarded as injurious to the human system.

If the results of Prof. Drown's experiments on the aeration of natural waters are to be accepted as conclusive upon this point,† then the claim for oxidation of dissolved organic matter and its conversion into nitrites and nitrates is a mistake. No such result will follow the aeration of water containing dissolved organic matter, but, as Prof. Drown shows, aeration may be beneficial in expelling from water objectionable gases in solution; as, for instance, sulphureted hydrogen, but no chemical reaction can be expected from simple aeration.

It will be noticed that the first step in the purification of water described by the writer's correspondent is the treatment with alum, and that the water is at rest for a period of from 5 to 30 minutes, to give time to the alum to act as a coagulent and precipitant. This would seem to indicate an attempt at intermittent filtration with the continuous filter, or would involve the alum treatment of water in settling tanks, somewhat after the style of the precipitating tanks used for the purification of effluent sewage.

A successful filter must remove both suspended and dissolved matter and the toxic properties in water, otherwise it will be of doubtful utility as a sanitary appliance, because the average citizen accepts such devices altogether upon the representation of the manufacturer, under the impression that he has a safeguard against disease from a water source, when in reality he has nothing of the kind, and his danger from water-borne disease may probably be as great after he filters his drinking water as it was before.

According to Prof. Baumeister,‡ we can safely drink a sewage-polluted water when the sewage and water are mixed in certain proportions, depending upon the amount of organic matter in the sewage and

* Parkes' "Practical Hygiene," 1892.

† Twenty-third Annual Report, Mass. State Board of Health.

‡ R. Baumeister, Cleaning and Sewering of Cities, 1891.

of that previously in the water. But he depends altogether on chemistry for the test of potability of the water, when it is well known that chemistry is powerless to reveal infectious properties or bacteria in the water. He states, upon German authority, that water may carry 2½ grains of organic matter to the gallon and still be potable. Looking at the question from a chemical standpoint, this may be true, but from a broad, sanitary standpoint any organic matter in drinking water known to be from a sewage source is unsafe.

The statement by Prof. Baumeister that sewage containing 29.2 grains of organic matter to the gallon may be mixed with river water containing 1.2 grains of organic matter to the gallon in the ratio of 23 galls. of water to 1 gall. of sewage, and the mixture be safe for drinking purposes, seems to me to be very dangerous, because the sewage may contain the germs of typhoid fever, which no amount of dilution can eliminate. Moreover, advice like this, instead of promoting the purity of water supplies and the public health, is calculated to impair both.

It is but fair to state that Prof. Baumeister is looking at the matter solely from the standpoint of sewage disposal into running streams, and it is doubtful if the selfish motive of ridding a community of sewage by generally the easiest and cheapest method should be allowed to prevail when certain disaster to those who may draw their drinking water from the stream below is bound to follow.

In another paragraph Prof. Baumeister says:

"The objection may be raised to these computations" (relating to sewage dilution) "that the limiting amounts of organic matter in potable water was not fixed under a supposition that a part of it was human excrement."

But all sewers receive some human dejecta, and this at times may contain disease germs, and these germs mixing with a so-called potable water are dangerous. Adapting to our purpose the memorable words of Mr. Lincoln, any water likely to be adopted for drinking purposes may be safe to all people at some times; it may be safe to some people at all times, but it may not be safe to all people at all times, and the protection of those who may at some time be susceptible to its deleterious influences should warn us against the use of any drinking water known to contain organic matter from a sewage source.

Without regard to the manner in which we obtain our drinking water, whether, as Mr. Rafter suggests, "from an absolutely uncon-

taminated source," by filtration, or by filtration and distillation combined, it should never be cooled by melting in it natural ice from an unknown source. No objection can be raised to the melting of artificial ice from distilled water in our drinking water; and, when this is not obtainable, natural ice can be safely used only by placing it in a receptacle separate from that containing the water.

Water is an essential to human existence, 90% of the liquid portion of the blood is water, and of the corpuscles or disks in the circulation nearly 70% is water. Of all the many articles of diet upon which we subsist, none is so important to the support of life as water. With all other articles of subsistence we are usually very careful, not only to demand the best, but to insist that they be absolutely safe to take into the human system; with water, however, we drink whatever comes most conveniently to hand, with no inquiry, and seldom a thought, as to its fitness for the purposes to which it is applied in the animal economy; and yet one of the most dangerous diseases, typhoid fever, can be established in the human system through the medium of drinking water. For, even in the few instances of its being traced to the distribution of a polluted milk, it has been shown that the remote cause or origin was in a typhoid-tainted drinking water.

In many States a human life has a fixed legal money value. The law of Ohio places the worth of a man's life at $10 000. If every fatal case of typhoid fever in the United States is multiplied by this amount the product will reach over $350 000 000 a year, a sum equal to one-third of the present National debt. And notwithstanding the appalling misery and loss of valuable lives from this one disease, typhoid fever would be unknown if the plainest and simplest rules of hygiene with reference to our drinking water were universally followed. In simple terms, if the typhoid germ or bacillus, as it is technically called, were excluded from our drinking water, the disease could not be established. While typhoid is not the only water-carried disease, to us it is the most important, if importance is to be measured by geographical extent, continuous presence and annual loss of life by disease. In the foregoing discussion of the quality of drinking water, while other objections may have been raised against the so-called potable water with which we are generally supplied, the main objection is to the possibility of its introducing the typhoid germ into the system.

Nature's process of purifying water is by distillation on a very large

scale. The waters of the lakes, rivers and sea are evaporated, the vapor ascends from the surface of the earth, is condensed in the clouds, and in due time returns to the earth as rainfall. After we have received the water again into our lakes and streams, or in the absorbent soil, we set about to pollute it with our sewage wastes, and, when thoroughly polluted, we drink it. This may be a very coarse way of stating the case, but is it not the fact? Nature attempts to supply us with a water free from dangerous organic matter and toxic properties, but we will not preserve it in this condition.

In regard to past efforts at water purification, and the attempt to build a standard of purity upon the reduced numbers of bacteria in the filtrate, certain facts have been established in connection with bacteria in water. Thus, the number is not a safe index of the quality of water. Well waters containing so few as four bacteria per cubic centimeter have been fatal to the lower animals, while lake water containing as many as 3 000 bacteria per cubic centimeter has produced no ill effects on the lower animals. Upon the other hand the number of bacteria is a fair indication of the amount of dissolved organic matter in water, but the determination of this by chemical tests is more reliable than to infer it from the number of bacteria. Generally, however, the water bacteria bear a close relation in numbers to the amount or proportion of dissolved organic matter.

While many attempts have been made and several well-known methods proposed to differentiate the typhoid bacillus from other bacteria found in water, none of these seems to be reliable, and the only certain test of the pathogenic properties of any suspected bacteria is by inoculation.

The ordinary water bacteria are not regarded as pathogenic, and pathogenic germs in a water sample are held to be adventitious, and not native to the water. This will partly account for the danger from a water containing few bacteria, and for the innocuous properties of some waters containing many bacteria, and emphasizes the belief now gaining ground, that numbers should not be received as an evidence of quality.

The introduction of a few water bacteria into a sample of distilled water may be followed by a large growth of the same species, but these cannot endure for many days, for lack of nourishment. If the water was absolutely sterile, and no organic matter imparted to it from the

atmosphere while introducing the bacteria, then no growth could occur, and in a short time the bacteria introduced would perish for lack of pabulum.

The typhoid bacillus and the cholera spirillum are not indigenous to water. Water is simply the carrier of these germs of disease, but owing to the difficulty of identifying them, especially the typhoid germ, no one can certainly say whether a suspected water contains the germ until inoculation tests have been made; and if pathogenic germs are found, then an expert judgment only can infer the presence of the Eberth bacillus, or some other bacteria having the same properties. However, if in the inoculation experiments simultaneous tests are made from pure cultures of the suspected bacillus and with the Eberth bacillus obtained from the spleen of one dead of typhoid fever, and the symptoms of the animals experimented upon are substantially the same, then it will be safe to declare the suspected water bacteria as the typhoid germ, even though its morphological and biological characteristics may not agree with the Eberth germ. Thus it may be a variety of the Eberth germ, or it may be a distinct germ capable of producing the same effects in the animal system. To illustrate this in a homely way, no one is likely to mistake beer for whiskey or *vice versa*, but both are known to produce intoxication. In like manner, two pathogenic germs may differ in their morphological and biological features enough to appear to be distinct species of bacteria, and at the same time possess similar toxicogenic properties.

It is unfortunate that cities are so unwilling to conduct such investigations of their water supply during epidemics of typhoid as will clearly demonstrate the condition of the drinking water at all times. As an illustration, one city of several is mentioned. During the later part of the year 1892 and early part of 1893 St. Louis was visited by an epidemic of typhoid fever, which increased the annual death rate from this cause 200 per cent. Investigations were made by the city authorities which clearly established the fact that the disease was practically confined to a district almost wholly supplied with water from the city mains; but, excepting this inquiry, which traced the cause to the Mississippi River water, no tests were made of the quality of the water at the time of the epidemic, or to compare it with the river water at other times when there was no epidemic of typhoid. There is no doubt that careful bacteriological tests would have shown the typhoid

bacillus of Dr. Eberth or Dr. Vaughan in greater numbers than usual in the water, or that the toxic properties developed by the germ when taken into the human system were then much more virulent than at other times.

To solve the question of an absolutely safe drinking water, the filtration to clarify the water should be combined with some process of distillation, and we shall have then, not only pure water, but water that looks pure, which is quite an object when you undertake to educate people upon the question of water quality.

As a matter of interest in connection with the subject of water quality and typhoid fever, the writer has compiled the statistics of typhoid from a number of our larger cities for the years 1890–91–92–93, giving the population, cases (when reported), deaths, and deaths per 1 000 of population (see Table A).

A comparison of the statistics in the table furnishes some interesting information. Thus the water drank in New York and Brooklyn seems to have been superior to that furnished to the city of Boston. Comparing Detroit with Buffalo, Cleveland, Chicago and Milwaukee, it appears that, while all depend upon the Great Lakes for their supply, the water drawn from the Detroit River is better than that from intake cribs set in the lakes a few miles from the shore, or at the foot of the lake, as at Buffalo. As a rule, the cities taking their water supply from the large rivers suffer more from typhoid fever that those that depend upon impounded water, like New York and Boston.

In Table B are given the data from epidemics of typhoid in the cities of Lowell, Lawrence and Springfield, Mass.; St. Louis, Mo., and Pittsburgh, Pa. The title and captions of the table fully explain its contents. Assuming the report of cases to be correct, the mortality from this disease, as shown by the column of percentage of fatal cases, is much greater in this country than in cities abroad.

TABLE A.

Typhoid Fever Statistics.

From the principal cities of the United States.—Compiled from Official Reports of Health Departments.

City.	1890.				1891.				1892.				1893.			
	Cases.	Deaths.	Population.	Deaths per 1 000.	Cases.	Deaths.	Population.	Deaths per 1 000.	Cases.	Deaths.	Population.	Deaths per 1 000.	Cases.	Deaths.	Population.	Deaths per 1 000.
Boston	.....	191	437 245	43/100	966	154	461 093	33/100	765	137	474 063	29/100	.....	148	487 397	30/100
New York	1 100	352	1 705 980	21/100	1 342	384	1 765 645	22/100	1 140	400	1 827 396	22/100	1 005	381	1 891 306	20/100
Brooklyn	.....	218	853 945	25/100	.....	174	880 780	20/100	.....	162	962 530	17/100	.....	165	990 891	17/100
Philadelphia	.....	666	1 046 964	64/100	.....	683	1 069 264	64/100	.....	440	1 092 168	40/100	.....	456	1 115 562	41/100
Baltimore	.....	241	434 151	55/100	.....	150	445 853	34/100	.....	193	458 350	42/100	.....	224	473 193	47/100
Washington	.....	208	250 000	83/100	.....	208	250 000	83/100	.....	183	260 000	70/100	.....	187	285 000	66/100
Pittsburgh	.....	.....	.....	.....	1 047	248	247 000	1	1 145	256	255 000	1	2 398	294	264 000	1 11/100
Buffalo	.....	.....	.....	.....	.....	129	255 664	50/100	.....	98	285 000	34/100	.....	112	300 000	37/100
Cleveland	461	182	277 488	65/100	349	155	299 475	52/100	376	167	309 243	54/100	281	153	322 932	47/100
Detroit	.....	41	230 000	18/100	.....	30	230 000	13/100	. .	117	230 000	51/100	.....	140	230 000	61/100
Chicago	.....	1 008	1 100 000	92/100	.....	1 997	1 300 000	1 53/100	.....	1 489	1 400 000	1 06/100	.....	670	1 500 000	44/100
Milwaukee	.....	73	220 000	33/100	166	77	233 333	33/100	196	76	245 000	31/100	382	95	260 000	37/100
St. Louis	.....	155	450 000	34/100	442	139	452 000	30/100	436	172	460 000	37/100	3 624	514	500 000	1 02/100
New Orleans	.....	50	254 000	19/100	.....	59	254 000	23/100	.....	53	254 000	20/100	.....	39	254 000	15/100
San Francisco	.....	176	300 000	58/100	.....	137	330 000	41/100	.....	113	330 000	34/100	.....	106	330 000	32/100
Cincinnati	.....	197	296 000	67/100	270	186	300 000	62/100	245	121	305 000	40/100	214	134	310 000	43/100
Louisville	.....	142	161 000	88/100	.....	130	161 000	80/100	.....	116	161 000	72/100	.....	135	161 000	84/100

TABLE B.

Typhoid Fever.

Statistics Showing Fatality of Epidemics in Lowell, Lawrence and Springfield, Mass., and Annually for Pittsburgh and St. Louis.

Locality.	Date.	Cases.	Deaths.	Percentage of fatal cases.
Lowell, Mass.	September, 1890	47	10	21
"	October, 1890	95	9	9.5
"	November, 1890	171	29	17
"	December, 1890	159	24	15.1
"	January, 1891	78	17	22
Total and averages		550	89	16.2
Lowell, Mass.	November, 1892	19	3	16
"	December, 1892	70	10	14.3
"	January, 1893	38	10	26.3
"	February, 1893	14	7	50
Total and averages		141	30	21.3
Lawrence, Mass.	November, 1892	14	4	28.6
" "	December, 1892	32	9	28.1
" "	January, 1893	72	3	4.2
" "	February, 1893	23	12	52
Total and averages		141	28	20
Springfield, Mass.	July, August, September, 1892.	155	32	20.6
St. Louis, Mo.	April, 1892; March, 1893	3 624	514	14.2
"	August, 1892	70	11	15.7
"	September, 1892	142	23	16.4
"	October, 1892	261	48	18.5
"	November, 1892	1 923	124	6.4
"	December, 1892	945	205	21.7
"	January, 1893	114	42	36.8
Pittsburgh, Pa.	1891	1 047	248	23.7
"	1892	1 145	256	22.4
"	1893	2 398	294	12.3

DISCUSSION.

DESMOND FITZGERALD, M. Am. Soc. C. E.—A paper on the quality of water supplies needs no apology to this Society when we consider the army of engineers who are engaged in works of construction and improvement connected with the furnishing of pure water to cities and towns. Mr. Hill has well stated in the opening of his paper that, however much other sanitarians may aid the cause of good water, to the engineer must finally come the designing of works for public supplies. If there is one fact more gratifying than another to sanitary engineers, it is that so much attention is now paid to questions connected with the quality of water. It was only a few years ago that the question of quantity was the principal one to which water engineers devoted their studies. Probably few outside of the specialists realize how varied are the questions that enter into this subject of the quality of water.

We have to begin with a large classification of waters, each of which is subject to its own particular kind of troubles, and many of these are so subtle that it requires a lifetime to understand them. But I do not know of a nobler occupation or profession to which a man can devote his life than that of the improvement of water supplies.

It does not seem to me that we depend upon seeing the actual germs of disease in the water with the microscope or by inoculation from water samples in order to satisfy ourselves that they are present. We have had in Massachusetts several epidemics of typhoid fever in cities taking their water from sources infected with the typhoid bacillus where the death rate has immediately declined on cutting off the polluted water. A remarkable case has recently been presented fully by Mr. Mills before the New England Water Works Association in a description of a new filtering plant installed in Lawrence to rid the water of typhoid germs.

I was recently called to a small town containing 1 300 people, in which over 100 inhabitants were down with typhoid of a malignant type, and of these more than 10% died. In a large institution situated in the town with a separate water supply of its own not one person was taken sick with the disease. Happily I had no difficulty in persuading this town to throw away its source of supply and adopt another pure and abundant source close at hand. Under these conditions, there were so many circumstances pointing to the water as the source of infection that it did not require identification of the actual bacillus in the water.

In many cases a great deal of study is given to purifying a water,

when the same amount of study put into the question of preventing the pollutions from getting into it would do more good. During the past ten years we have devoted a great deal of time and money to this end on the Boston Water Works. The sewage from many of the towns has been pumped entirely out of the water-sheds and improved methods of construction have been adopted for the basins and storage reservoirs for the purpose of improving the quality of the water. We are now engaged in studying swamps existing on the water-sheds and providing plans for draining them, and many observations have been made upon the color of the waters coming from swamps and estimates formed of the probable colors after the improvements have been carried out. There is still, however, something to be said in favor of filtration in the case of almost any surface supply, however well guarded at the sources, and I look in the future to see filtration plants in more general use.

As is the case in many other large cities, we obtain our water supply in Boston by collecting and holding back water from streams during the wet months of the year, in order to distribute it during periods of deficiency in the flow or of long periods of drought. We have, of course, designed our storage so as to cover the longest drought in the past, of which we have a record, and we have made our storage sufficient to carry us through that drought; but it has been strongly impressed upon my mind recently that this is not sufficient to provide a uniform quality of good water. In order that this may be accomplished we must have a much larger amount of storage.

As is well known, surface water improves in quality when kept for a long time in thoroughly constructed basins which are free from organic matter. Now, when water is drawn out from these storage reservoirs at the end of the period of drought and the streams begin to resume a larger flow, then the city has to be supplied with water which has not had the advantage of long periods of storage. From this cause it is not possible always to distribute water of a uniform quality, unless a large surplus of storage is supplied, and it seems to me important that where a city or town is provided with water by means of equalizing the supply of a stream or by drawing from a natural lake, it is necessary that a very much larger amount of storage should be provided than that necessary simply to carry the town or city through the drought.

If the reports of the Boston Water Supply Department for the past few years are examined, it will be found that the number of organisms existing monthly at the surface, in the middle, and at the bottom of all our lakes and storage and distributing reservoirs are published in tables, and that the colors of these same waters and their temperature are given. These monthly averages are made up from weekly examinations. It will also be found that we have a well-equipped laboratory

devoted to microscopic work, and that we have a considerable filtration plant for the purpose of experimenting upon different methods of filtration. In fact, we spend from $12 000 to $15 000 a year upon experiments and analyses connected with questions affecting the purity of the water. This work has naturally revealed many facts of which we were not before aware. There may be some who think that money invested in this way is thrown away; but I think we may very well leave the future to decide this question. We feel, in Boston, that we have made a good investment in this work.

It seems to me questionable whether Mr. Hill's figures for the cost of separating the drinking water from the rest of a supply are sufficiently large. It has not been considered that we can accomplish this result in Boston with so small an expenditure per gallon.

Aeration has been referred to in this paper. It has been found on the Boston Water Works that no amount of aeration will affect the quality of the water, although we have more organic matter in the water than I should like to see. The truth is that the water contains sufficient oxygen in its natural condition, so that the addition of any more has no effect whatever. On the other hand it is true that there are many waters which are so deficient in oxygen and in which the organic matter is in such a condition that aeration produces wonderful effects in a very short time.

It does not seem possible to provide general rules which will apply to all waters. However much we do not know, there is one thing of which we feel sufficiently certain, and that is as to what good water really is; and this is the goal upon which we should keep our eyes and the standard to which we should work.

Charles Francis, M. Am. Soc. C. E.—What may be called the germ of the typhoid bacillus may be generally found in the larger intestines of healthy people. These germs being introduced into the upper or smaller intestines through the medium of drinking water and finding there suitable pabulum, develop into the true typhoid bacillus.

William E. Worthen, Past President Am. Soc. C. E.—As engineer in charge I have just completed a small water works at Southampton, L. I., in which the principle has been adopted of not exposing the water from the driven wells to the light till it is drawn by the takers. From the wells the water passes through the pumps into air-tight receivers or tanks of steel 6 ft. 6 ins. diameter and about 50 ft. long. There are three tanks which are filled at the maximum pressure of nearly 100 lbs. One of these receivers is open always to the village service; the other two are closed under the 100-lb. pressure. When the pressure in the first receiver falls to nearly 40 lbs., one of the reserved tanks is opened to raise the pressure in the mains and after another fall the third tank is opened. For fire purposes the tanks can be opened and adequate pressure secured promptly.

The water is strongly aerated by the compressors, which maintain the air pressure and volume, and the water is cool for domestic use. I am anxious to see its sanitary effects, as it will probably prevent the development of *confervæ*, and shall look to the report on vital statistics. With regard to the growth of microscopic organisms, I do not know of any standard authority, but think that sterilization should be used carefully, that "numerous bacteria exist in the digestive canal of a man in good health, and that they are not only innoxious, but they play an active part in gastric digestion and especially in the transmutation of albumens into peptones"; that they are necessary for the support of the white blood corpuscle and consequently of the red. My suggestion would be, sustain your own phagocyte and look to the effects as they can be seen naturally rather than to the present results of microscopic observation. It takes something more than microbes to produce ptomaines, there is a necessity of some pabulum and condition, and good health must depend largely on the surroundings and habits.

CHARLES H. SNOW, Assoc. M. Am. Soc. C. E. (by letter).—Mr. FitzGerald has spoken of typhoid fever in a small town where those not using the common water supply were totally exempt from the disease. Such instances are common and furnish the most forcible argument for good water kept good. An interesting incident of the same kind was afforded by a small town in which I was located for some time.

The town was upon the sides of, and in the valley between, two hills. It had two sources of water supply. Mine water pumped from about 500 ft. below the surface, and surface water collected in wells. The mine water was freely given to all who sent for it, and those using it were not confined to any particular district, but were more or less scattered throughout the entire town. A miner having contracted typhoid fever elsewhere sickened upon one of the hill slopes, whence the fever presently spread over the entire population of 4 000 to 5 000 people. In one house sixteen cases developed. There were no instances of fever among those using mine water. As an illustration of the ignorance frequently displayed respecting water, while the fever was prevalent wells sealed by the Local Health Board were broken into by families insisting on the use of their own supply. I also recall seeing people dipping water from a small brook running through the town, which was practically a sewer, that a trip to the mine for water might be saved.

As the province of the physician is to cure disease, so that of the engineer is to prevent it, and a more pronounced method of popular instruction would be found useful in accomplishing this result, and might come within his province.

S. WHINERY, M. Am. Soc. C. E. (by letter).—Mr. Hill has given the Society a very valuable paper upon the subject of which he treats. While he does not claim that there is much in it that is new, he pre-

sents a valuable summation of the present state of knowledge on the subject, and some pertinent suggestions as to the sanitary defects in present methods of water supply, and the means that are available for securing pure drinking water, and of avoiding its contamination before and after being collected or stored for use. From the evidence now in our possession, the problem of securing an uncontaminated supply of water for domestic use, is not only not yet practically solved, but is every day becoming more difficult of satisfactory solution. Unless collecting grounds are fully controlled, and carefully watched and guarded, there can be no certainty that uncontaminated water will be secured. As the population of the country increases and land becomes more valuable, it will become more difficult and expensive to secure control of collecting grounds, and to guard the supply against contamination. Even under the most favorable conditions, the danger of pollution will be very considerable.

The evidence is accumulating that we cannot rely on artificial filtration to remove from drinking water the germs and their spores that cause specific diseases. It was for a time supposed that filters of the Pasteur type could be depended upon to entirely remove deleterious elements from water, however polluted. It is now conclusively proven that in this we were but leaning on a broken reed. Combined filtration and oxidation by the use of filtering beds of sand and coarser materials has given great promise of success, as recently conducted in a painstaking and scientific manner under the careful supervision of competent experts and engineers. What the result would be under ordinary conditions of practice is at least problematic. The possibilities of lack of intelligence, carelessness, and management under engineers or superintendents more noted as ward politicians than as civil engineers or sanitary experts, are not pleasant to contemplate. Probably very few of us, in the present state of knowledge on the subject, would be willing to trust the health, and possibly the lives, of ourselves and our families to the use of drinking water known to be, in its natural condition, polluted and dangerous, if the only safeguard was purification by this method, under such management as too frequently controls the water supply of our cities.

The possibility of securing a perfectly safe water supply from deep wells in or near a great many of our cities, especially those situated within the glaciated regions of the country, is worthy, I believe, of far more attention than has been given it in this country. The evidence is accumulating of the existence of a great number of considerable streams of water flowing in the beds of pre-glacial streams, through beds of sand and detritus, so far below the present surface that the water has been subjected to the most perfect filtration, so that it is pure and wholesome beyond question. Such water supplies are often, though not so frequently, found in regions outside of those subjected

to glacial action. The possibility of securing such supplies should be thoroughly investigated in the vicinity of every city where there is any doubt about the purity of the supply of surface water. To this end, the discovering and mapping out of pre-glacial water-courses should receive more attention than it has heretofore, over the whole region of glacial action.

To me, the most important and suggestive part of Mr. Hill's paper is that relating to the purifying of water by boiling and distillation. This is not, of course, a new idea, but it is recalled to the attention of engineers by Mr. Hill at a most opportune time. Distillation is Nature's own method of water purification. Our standard of purity of potable waters is, and will continue to be, water distilled by the heat of the sun and condensed from the clouds by Nature's processes. The cup of water we collect as it falls from the clouds is, barring the slight possibility of contamination by germs and impurities floating in the air, absolutely pure and wholesome for domestic use. No matter how impure it may have been before its distillation, it may now be used with perfect safety. It is possible that a portion of it may have come from the filthiest cesspools, another portion from the excrement from fever hospitals or the waste from diphtheria wards, and still another portion may have come from the filthy haunts of cholera patients in the far East, yet we may now drink it with impunity.

Distillation is the one method of water purification that all are agreed is perfectly effective and reliable.

The only question about the practicability of this method is that relating to cost. Mr. Hill has treated of this part of the subject with considerable detail, and has shown that a supply of absolutely pure water for domestic purposes can be secured at a cost, which, considering the great benefit that would result, is certainly worth incurring. I believe, however, that the cost may be materially reduced below Mr. Hill's estimate. It will be noticed that he contemplates condensing and cooling the distilled water by surface condensers cooled by the 97 or 98% of water that must be provided for purposes other than drinking. This would mean the wastage of all the heat given up in the condensation and cooling of the distilled water. If, instead of thus wasting this heat, it be utilized for heating the water to be distilled, the process would be cheapened to that extent. This might be readily accomplished by passing the steam to be condensed and the hot condensed water through pipes surrounded by the incoming water on its way to the boilers. Just how much of the original heat could thus be returned to the boilers, I am not prepared to say; but it is, I think, safe to say that 40% of it could be thus saved and re-utilized. Assuming that this is possible, it would not only reduce in the same ratio the cost of fuel and attendance, but the cost of the plant for distillation also. Making

such modifications as this assumption will allow, and making some other changes in Mr. Hill's estimate as seem warranted, we shall have the following as the cost of treating 1 000 000 galls. per day:

Cost of plant for distillation....	$135 000
Cost of separate system of pipes for a city of 160 000 population.....	450 000
Cost of plant for aeration of water if thought necessary.....	15 000
Total.....	$600 000

COST OF OPERATING FOR ONE YEAR.

Interest on investment at 4 per cent.....	$24 000
Repairs and renewals at 5 per cent.....	30 000
Cost of fuel.....	91 500
Cost of labor and superintendence.....	24 000
Total.....	$169 500

which, divided by 365 000 000 galls., gives as the cost of purification per 1 000 000 galls, about $465.

I have no data at hand as to what amount of water would be necessary for drinking and such other domestic purposes as would insure freedom from specific diseases caused by contaminated water, but I think it would be safe to assume that the amount would not exceed 6 galls. per capita. On this assumption 1 000 000 galls. would be sufficient for a city having a population of 160 000, and the cost per capita per day would be less than three-tenths of 1 cent, and the cost for a family of five persons would be 1½ cents per day, or about $5 50 per year.

It is to be anticipated that the most serious difficulty in operating such a system will be found in the proper regulation of the use of the purified water. On the one hand, some families would be disposed to use the pure water for other than the purposes for which it is intended, and others, either from carelessness or to avoid the cost, would be likely to omit its use. The first difficulty might be met by the use of meters at every house, and for the use of such meters a reasonable rental would have to be charged.

The opposite difficulty could, perhaps, be best met by requiring by municipal ordinance the use of the pure water for certain stipulated purposes, and making it the duty of sanitary inspectors to see that the ordinance was complied with.

What I have said is intended only as an outline of what might be done in this way toward the furnishing of an absolutely pure supply of water for domestic use. The subject is of such great importance as to merit, in my opinion, the most careful consideration and investigation of the system suggested, by water-works' experts and sanitary engineers.

WILLIAM P. MASON, Esq. (by letter).—The author of this paper appears to be a believer in the power of water to spread disease, but some of the statements and quotations advanced by him would certainly go far to unsettle the public mind and cause lack of faith in the teachings of some able masters.

He says: "While water is held to be a carrier of disease germs, the writer is not aware that any investigator has ever claimed to have seen these germs in water, even under the highest powers of the microscope; and the evidence that water is such a carrier of pathogenic bacteria is obtained by inoculation from water samples of nutrient media in test tubes or on culture plates."

"The typhoid bacillus in water has never been seen with the microscope without previous cultivation of the germ in nutrient media. Nor has it ever been demonstrated, so far as the writer is aware, that the presence of bacilli in water can be proven, excepting by delicate and difficult bacteriological processes."

That single individuals of the Eberth bacillus should escape direct detection is hardly to be considered surprising, in view of the enormous volumes of water in which they are suspended. However difficult the processes of modern bacteriology may be for a tyro, it is hardly just to consider them unreliable in the hands of such experts as Koch, Pasteur or Eberth; and, if any one of these men, or of many others who might be named, should state that he had secured pure cultures of a specific germ under circumstances which excluded the possibility of extraneous contamination, we should be exceedingly liable to believe him.

Again: "It is well understood that the infective element of typhoid fever can be present in water and the chemical test be powerless to disclose it."

True enough, but it does not complete the story. During an investigation following a serious outbreak of typhoid fever in the Tees valley, England, the medical officer of the Local Government Board, London, caused preparation to be made of samples of pure water to which small quantities (50 and 25 parts per 1 000 000) of typhoid dejecta had been added, and these samples were then submitted to prominent water analysts for examination. No results upon which an adverse report could be based were obtained. The contaminated waters were pronounced pure. It must be remembered that the polluting material, as weighed, being very largely water, the pollution appeared greater than it really was. Fifty parts per 1 000 000 of the typhoid dejecta corresponded to only 4 parts per 1 000 000 of total dry residue. As a natural

result of these experiments, the purely chemical methods of water examination received very severe criticism, and the advocates of the exclusively bacteriological processes were correspondingly elated, for here were known instances of fatal contamination which the chemists had failed to diagnose. Let this, however, be said in defence. In cases as they occur in practice a serious addition of typhoid dejecta has much that is associated with it of a comparatively inoffensive character, but which reacts with the chemical reagents and tells the tale of sewage contamination, although the analyst cannot venture to state the exact nature of the source from which the pollution is derived.

Not long since the writer claimed that the river water furnishing a large eastern city was contaminated with up-stream sewage, the opinion having been based, not alone upon an analysis of the water at the intake, for the river was large and the consequent dilution great, but upon the difference between that analysis and one of the water taken from above the sewage inflow. The difference was small, but it was noticeable, and there was no other sufficient explanation of its existence than the one given. Later on typhoid fever broke out in the upper valley, and epidemics developed not only in the city in question, but in all the neighboring towns using the river water for supply. Closely related cities and towns, which received their water from other sources, were not affected. Space does not permit of giving details, showing how clearly the case stood against the river water, but it is interesting to note that typhoid germs were most carefully sought for and were not found. That they were nevertheless present, there can be but little doubt. Chemical analysis in this instance did certainly not detect the presence of typhoid, but what it did do was to warn the people, months before the typhoid appeared, that they were drinking diluted sewage, and that they must beware of the time when that sewage should come from pathogenic sources.

The paper in question goes on to say :

"The popular impression that the Koch, or Finkler and Prior, comma bacillus is the cause of cholera is fallacious, or, at least, not proven. The same remark applies to the typhoid bacillus of Eberth. The proof is still wanting that this will cause typhoid."

This last is a quotation from Sternberg's "Manual of Bacteriology," but it is very misleading because it is incomplete.

What Sternberg really says is this:

"Recent researches support the view that the bacillus described by Eberth in 1880 bears an etiological relation to typhoid fever; and pathologists are disposed to accept this bacillus as the veritable germ of typhoid fever, notwithstanding the fact that the final proof that such is the case is still wanting.

"This final proof would consist in the production in man or in one of the lower animals of the specific morbid phenomena which characterize the disease in question, by the introduction of pure cultures of the

bacillus into the body of a healthy individual. Evidently it is impracticable to make the test upon man, and thus far we have no satisfactory evidence that any one of the lower animals is subject to the disease as it manifests itself in man."

Now, that is a very different statement, and conveys a meaning greatly unlike the one suggested by the partial quotation referred to.

The paper again says :

"Absolutely healthy persons have been known to reject the Eberth bacillus in their excrement, showing such, probably, to be in the intestines at all times."

This is an error. The *bacillus coli communis*, which closely resembles the typhoid bacillus, is constantly present in the intestines of healthy persons, and may lead to confusion, but no position such as the above quotation indicates is now occupied by bacteriologists. In this connection Sternberg (an authority frequently quoted in the the paper) says : "No competent bacteriologist, so far as I know, has claimed to find the Eberth bacillus in the fæces of healthy individuals."

As to the doubt thrown upon the correctness of the view that Koch's comma bacillus is the cause of cholera, the work of Sternberg will hardly endorse it. In this connection Sternberg says:

"The etiological relation of this spirillum to Asiatic cholera is now generally admitted by bacteriologists." And also : "The most satisfactory evidence that this spirillum is able to produce cholera in man is afforded by an accidental infection which occurred in Berlin in the case of a young man who was one of the attendants at the Imperial Board of Health when cholera cultures were being made for the instruction of students."

As to the statement in the paper that "fatal cases of typhoid have been attended with none of the Eberth bacillus in the fæces, or in the intestines, the seat of the disease," it is to be noted that Gaffky's investigations show it to be by no means a serious objection. He considers the technical difficulties surrounding a hunt for the bacillus, in some few instances, so considerable as to readily account for a small percentage of negative results; and he cites instances where he found the "germ" after an amount of patient search which extended far beyond the point where the average observer would have ceased work and placed a negative report upon record.

Finally the paper has much to say upon the imperfections of modern filters and the danger of using water therefrom. It goes without saying that pure water is better than purified water, but then the former is often unattainable and we have to do with the latter or go without.

Especial stress is laid upon the fact that even when the filtration is so successfully accomplished as to leave in the filtrate only one or two bacteria per cubic centimeter, yet "a person may imbibe from 250 to 500 bacteria in drinking a single glass of water, some of which may be

pathogenic and produce typhoid fever or some less dangerous disease." Such a degree of excellence in filtration as the obtaining of a filtrate with only one or two bacteria per cubic centimeter is, indeed, rarely attained; yet the public have a right to look with confidence upon a plant which does not pretend to accomplish half that amount of purification.

Consider for a moment what the Altona filters did for that city during the Hamburg cholera epidemic of 1892. The Altona water was taken from the Elbe River at a point below the outfalls of sewers carrying the cholera-infected sewage of 800 000 people. Yet Altona had no cholera (except imported cases), while Hamburg was scourged by it. The cities are practically one, a stranger being unable to tell the dividing line.

Take the numbers showing the efficiency of the Altona filters during one month of 1892.

The bacteria in the raw Elbe water per cubic centimeter varied from 9 370 to 44 140, with an average of 28 667. The average number in the filtered water was 90. This meant a removal of 99.69% of germs of all kinds, 0.31% still remaining. The filtrate was by no means sterilized, but the city was protected from a cholera epidemic under circumstances trying in the extreme. As to the efficiency of sand filtration for water purification, the following figures are given for results found at the Lawrence experiment station, the filters having been operated with water containing known quantities of bacteria:

Rate in gallons per acre daily.	Kind of bacteria added.	Per cent. removed.
1 500 000	B typhi. abdom.	99.93
3 000 000	B. prodigiosus.	99.95

This reduction of the number of germs in a given volume of water is possibly equivalent to a dilution of the unfiltered water with a very large volume of a pure supply, and in this connection the writer of the paper says: "Dilution may reduce the chances of any single individual imbibing a fatal germ, but the germ itself will be just as dangerous when it is imbibed."

This is, doubtless, true, if the individual be especially susceptible, for it has been experimentally shown that a single germ may produce fatal results when injected into an animal very prone to the special disease, but as it has been also shown that when the animal is not very susceptible, the "dose" of bacteria has to be enormously increased to produce any result. We incline to believe that some similar reason may account for the apparent immunity of that fraction of a community which has been equally exposed, but which escapes contagion.

What the paper says regarding the unsatisfactory results observed

where household filters are in use is unfortunately very true, but the fault is more commonly with the attendant than with the filter. The common belief is that a filter, once established, is good for all time, and I could tell tales of what I have seen in otherwise well-organized establishments that would stagger belief. I do not approve of general household filtration, as I believe purification can be better and more cheaply done on the large scale by the municipal authorities, but I cannot think that the Pasteur filter should be swept aside like the worthless contrivance the paper calls it. My experience is that, with proper care, it is efficient. Extended tests were made with it for the Connecticut Board of Health in 1892, which show that it may be depended upon, if the porcelain cylinder be cleaned and sterilized once a week.

Freundenreich has obtained similar results, and has also shown that the length of time during which the filter is efficient depends upon the temperature.

JOHN W. HILL, M. Am. Soc. C. E. (by letter).—The one grand proposition in connection with the quality of water supplies is that a polluted water is the immediate or original cause of typhoid fever and the typhoid symptoms in typhoid malarial fever, and that a water at all times wholly free from the typhoid bacillus can never produce typhoid when used as a beverage, nor in any other way.

Such water is very difficult to find in Nature, or, being found, it is difficult to preserve it free from contamination.

Water gathered at great elevations above habitations and the operations of husbandry, and impounded in large deep reservoirs, is perhaps the nearest approach to sterilized water in Nature which we can hope to make.

Rivers which receive sewage at any point above or at short distances below water-works intakes can never be regarded as safe sources for drinking water. The same statement applies, but generally with less force (excepting Lake Michigan at Chicago), to lakes which are the outfalls for town sewage.

Sand filtration abroad has generally been attended with good results, but it cannot be relied upon to remove all disease germs, and in this country, from my own experience, the continuous sand filter as usually operated is not to be depended upon as a safeguard against disease germs in water. From some investigations which I am now making of the water of the Passaic River, N. J., I find enormous growths of bacteria on gelatine and agar plates, even after the water has been passed through one of our celebrated mechanical filters. Plates being inoculated simultaneously from unfiltered and filtered water, the relative growths of bacteria from the filtered water is very startling. The results of the investigations mentioned above when completed will be published in due time in one of the engineering journals.

In replying to the criticisms of Professor Mason, the writer believes

that water is the carrier of the typhoid and other disease germs, and he is willing to accept the present evidence as proof of this. There is no desire to "unsettle the public mind and cause lack of faith in the teachings of some able masters," and if there is anything in the paper which rejects the conclusions of Eberth, Koch and other investigators of the typhoid bacillus, the writer must confess to such a degree of obtuseness as not to be able to recognize it. If the writer has not made his position clear upon this question in the paragraph at the bottom of page 135 *et seq.*, then the fault lies in the choice of language and not in intention.

In stating that the proof is still wanting that the Eberth bacillus will cause typhoid, the reference was made to Dr. Sternberg's excellent "Manual of Bacteriology," where those who may be interested in this phase of the water question can examine the authority at their convenience and draw their own conclusions.

It might have been better to quote at length from Dr. Sternberg's work, but it was not considered necessary, and would not have changed the substantial fact that "the proof is still wanting" that the Eberth bacillus will cause typhoid in man, however confident Dr. Sternberg, Prof. Mason, and others may be that it will. In this opinion the writer shares, but until inoculation experiments have been made upon man (and this is obviously impossible in an enlightened and humane age), there will remain some foundation for the opinion so often expressed of the fallibility of the germ theory of disease. While the evidence clearly shows the connection of the typhoid bacillus of Eberth with the typhoid fever symptoms, and probably shows it as the cause of typhoid, the positive evidence can be had only in the manner pointed out.

That the processes for the differentiation of the typhoid bacillus from other water bacteria are both "difficult and delicate," even in the hands of a master, Professor Mason is referred to Dr. Vaughan's "Bacteriological Study of Drinking Water," 1892, and to Dr. Sternberg's "Manual of Bacteriology," page 349, last paragraph, as well as to his own paper on "Some Cases of Drinking Water and Disease," 1891, when, notwithstanding his careful attempts at cultivation of the typhoid bacillus from the infected waters of the Mohawk and Hudson rivers, he failed entirely to find the germ. There is no doubt of the typhoid bacillus being in the water at the time of its examination by Professor Mason, but his attempts to show the existence of it were entirely negative. He gives a satisfactory reason for this, but his reason only proves that an attempt to demonstrate the existence of the germ in water is very difficult, and he is undoubtedly aware of the fact that the tests for the germ are very delicate and not very reliable.

The paragraph quoted by Mr. Mason on page 165 was, upon the

advice of Dr. Sternberg, withdrawn before the paper was read at the Convention, and the following paragraph was substituted:

"In order to approach the question of water pollution properly, it must be borne in mind that while polluted water is held to be the cause of certain diseases, exactly how it acts on the human system is not well known. Bacteriologists generally regard the Koch cholera bacillus and the Eberth typhoid bacillus as the causes of these diseases, but this view is not shared by all physicians as it should be if the proof of cause was sufficient; although common prudence should decide us in rejecting any water known to contain the cholera or typhoid bacilli, whether these germs be regarded as the cause or result of disease, since they indicate the presence of the cause even if not themselves the cause."

In regard to the remarks upon the incompetency of any known method of filtration to prevent typhoid fever, the writer can only add to what he has already stated in discussing this aspect of the quality of water, that while filtration may mitigate, it cannot be depended upon to wholly remove the evils of a polluted water. Thus the removal by filtration of 99% of the bacteria is accompanied by a reduction of 75% in the typhoid fever death rate, showing that the 1% of bacteria remaining in the water are as virulent in a pathogenic sense as 33% of the bacteria removed. Professor Mason has stated* that during the epidemic of typhoid fever in Albany and vicinity (1890–91) "boiling of water for drinking purposes was recommended, and no typhoid developed among families who followed the recommendation," clearly indicating that absolute safety from a water of known pollution lay in the direction of sterilization and not in the direction of filtration. This, in short, is the writer's position with reference to the problem of eliminating typhoid fever from the list of diseases by which we are now confronted. Let all polluted water be properly sterilized and there will be no typhoid among the people who drink and cook exclusively with such water.

* "Notes on Some Cases of Drinking Water and Disease." Professor William P. Mason, 1891.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

725.

(Vol. XXXII.—August, 1894.)

TEQUIXQUIAC TUNNEL, VALLEY OF MEXICO.

By ALBERT JOHNSTONE CAMPBELL and FREDERICK WILLIAM ABBOT, Assoc. M. Am. Soc. C. E.; A. M. Inst. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

General History and Description of the Work.—Ever since Cortes established the present city of Mexico on the site of the ancient Aztec Venice, the problem of the drainage of the Valley of Mexico may be said to have occupied the attention of its inhabitants. Numerous have been the projects for dealing with the difficulty, and very large amounts of money have been spent and much work done since the time referred to, work which in some cases has been partially successful or which at any rate has tended (aided by the changes in the rainfall of the district, contraction of the area of the lakes, etc.) to modify considerably the old conditions and to simplify somewhat the problem. It would take too long to enter into this past history in proper detail.

In modern times and during the Empire of Maximilian the project now in course of execution was commenced, and several of the shafts on the line of the existing tunnel sunk to a considerable depth, and machinery and expensive buildings in connection with the work erected. The fall of the empire and the years of trouble for the country that followed, put a complete stop to the works, and it was not until 1885,

when a special Commission or Drainage Board was formed by General Diaz, that work under the direction of Mr. Espinosa, the Government Engineer, was again commenced with any vigor. Want of funds however, prevented any great progress being made until March, 1888, when arrangements for a loan were completed and the work taken in hand by the present contractors, Messrs. Read & Campbell. On the transfer of the work by the Government, the contractors found 1 639 yds. of tunnel completed at the northern or open end and an aggregate depth sunk in the various shafts of some 2 937 ft., four of the shafts being down to tunnel level in the completed section, the remainder, as was proved later, having reached the level at which water was to be encountered in large quantities. The original time allowed for the completion of the work was extremely short and gave rise to the attempt to work from all the shafts at once with a pumping installation at each, as well as from the open end. The quantity of water had, however, been completely underestimated owing to the impossibility, from the nature of the ground, of obtaining reliable data, and this plan of working had to be given up, as also an attempt to prolong the tunnel some 4 miles at the southern end with a view to replacing the canal section, where the depth of excavation exceeded 60 ft. At one time the quantity of water, being raised in several of the shafts, amounted to 1 000 galls. per minute, and the enormous expense was entirely out of proportion to the advance made.

After a number of modifications of the contract the contractors notified the Government that they could not continue at the prices agreed on, nor on the conditions as to time, and finally in March, 1892, an arrangement was entered into by which the contractors continued to carry on the work on behalf of the Government as managers and administrators.

The small size of the shafts, the shape of the tunnel and the character of the ground had all been obstacles to the carrying out of the work in the three years as originally proposed, coupled with the loss of time due to the wrecking of a steamer off Vera Cruz carrying the heavy pumping machinery for the deeper shafts. As regards the shafts it may be mentioned that they were designed 7 ft. by 10 ft. inside dimensions, with an 18-in. lining of brickwork, and, at the time of the turning over of the work to the contractors, were mostly sunk more than half of the total depth required, but temporarily abandoned.

On the section of 6¼ miles of tunnel under construction the shafts are 24 in number, being spaced about a quarter of a mile apart with an average depth of some 175 ft., the deepest being 300 ft. and the shallowest 65 ft. deep.

The city of Mexico is situated on the central table-land of the Republic at an elevation of some 7 500 ft. above sea-level and at the extremity of a large flat valley surrounded by mountains, through which there is practically no exit for the water falling in this basin. The city is at present drained into Lake Texcoco, one of the lakes surrounding the city, but there is little fall even in the dry season, and in the wet season the waters frequently back up in the sewers and cause inundations in the streets. Various palliative measures, such as pumping at the outfall of the sewers, etc., have been adopted which have somewhat modified the evils, but nothing but the completion of the tunnel at present under construction, coupled with proper sewering of the city, can ever cure the existing evils and make the valley and the city what they should be, with the delightful climate and situation. The object of the works is therefore two-fold, to control the water in the lakes and in the valley, getting rid of any injurious surplus, and to afford an outlet for the storm waters and sewage of the city proper.

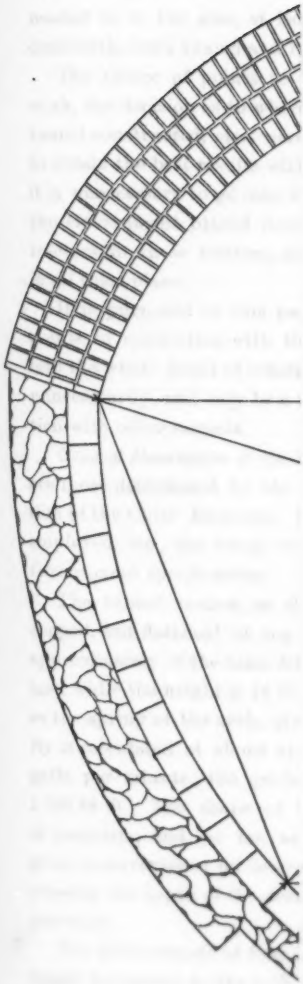
The works consist of a canal some 35 km. long, starting from the city gates, and a tunnel with a length of some 10 km. The canal varies in depth from 5.5 m. to 20.5 m. at the junction with the tunnel.

In March, 1892, the Drainage Commission decided to concentrate, as far as possible, the pumping machinery at the shafts at the northern or open end of the tunnel, and to devote special attention to a vigorous prosecution of the bottom heading with a view to connecting the various shafts as speedily as possible, and of so affording an outlet for the waters through the open end of the tunnel. As time was not such an important element in the contract, and, further, as a great many of the most heavily watered shafts had now, in spite of great difficulties, been sunk and the tunnel in part built from them, this scheme promised to give the best and most economical results. At the date of this change the back of the difficulties had been broken, the tunnel was in active construction at numerous points, and the organization perfect in every respect.

This change in the plan of working was largely due to Mr. J.

Limantour, President of the Drainage Board (now Minister of Finance), who insisted especially on a more vigorous prosecution of the bottom heading at any cost, although at that time the results obtained in driving the heading did not appear likely to reach anything like those ultimately obtained. When this plan was commenced there was about 1½ miles of the tunnel completed at the open end, which afforded an excellent outlet for the water. While the bottom heading was being pushed from one shaft to another, no other work was, as a rule, attempted in the same run of ground, as it was found that it delayed more or less the progress of the heading. As soon as two shafts were connected, tunneling could be commenced at once between them, providing care was taken not to block the water and so stop work in the heading which was being driven ahead to connect with the next shaft to the south. In order to make speedy tunnel progress, it was necessary to obtain as many working faces as possible by the construction of break-ups or intermediate sections of tunnel between the shafts, break-ups having been used by the contractors previously with great success; and so, as soon as a tunnel was started from the two shafts, some convenient spot in the heading between the shafts would be selected and break-ups made through the heading and a length of tunnel opened, by which means two more faces were obtained to work from. The number of these break-ups depended on circumstances, on the nature of ground, etc.; for instance, between Shafts Nos. 14 and 13, one break-up was used; between Nos. 14 and 15, two break-ups, and between Nos. 15 and 16, three break-ups; it was found, however, that two was the best number for convenient working. When the deepest shaft (having a total depth of 300 ft.) was in operation, there were, in working one regular tunnel face towards the north or open end, and one to the south, three break-ups, and then the regular face of Shaft No. 16, north; the faces were divided between the two shafts, and No. 17 had, therefore, to deal with one face to the north and one face to the south, and also a break-up and a half, or three faces, or in all, five faces, a large number for a shaft of such depth, and of such a small section.

By means of these break-ups the progress of the tunnel was very materially increased, as each face would average 60 to 90 ft. per month, making it possible to join the tunnel between two shafts in about three months; where the double-length system (mentioned later) was employed, better progress was made.



when a special Commission or Drainage Board was formed by General Diaz, that work under the direction of Mr. Espinosa, the Government Engineer, was again commenced with any vigor. Want of funds however, prevented any great progress being made until March, 1888, when arrangements for a loan were completed and the work taken in hand by the present contractors, Messrs. Read & Campbell. On the transfer of the work by the Government, the contractors found 1 639 yds. of tunnel completed at the northern or open end and an aggregate depth sunk in the various shafts of some 2 937 ft., four of the shafts being down to tunnel level in the completed section, the remainder, as was proved later, having reached the level at which water was to be encountered in large quantities. The original time allowed for the completion of the work was extremely short and gave rise to the attempt to work from all the shafts at once with a pumping installation at each, as well as from the open end. The quantity of water had, however, been completely underestimated owing to the impossibility, from the nature of the ground, of obtaining reliable data, and this plan of working had to be given up, as also an attempt to prolong the tunnel some 4 miles at the southern end with a view to replacing the canal section, where the depth of excavation exceeded 60 ft. At one time the quantity of water, being raised in several of the shafts, amounted to 1 000 galls. per minute, and the enormous expense was entirely out of proportion to the advance made.

After a number of modifications of the contract the contractors notified the Government that they could not continue at the prices agreed on, nor on the conditions as to time, and finally in March, 1892, an arrangement was entered into by which the contractors continued to carry on the work on behalf of the Government as managers and administrators.

The small size of the shafts, the shape of the tunnel and the character of the ground had all been obstacles to the carrying out of the work in the three years as originally proposed, coupled with the loss of time due to the wrecking of a steamer off Vera Cruz carrying the heavy pumping machinery for the deeper shafts. As regards the shafts it may be mentioned that they were designed 7 ft. by 10 ft. inside dimensions, with an 18-in. lining of brickwork, and, at the time of the turning over of the work to the contractors, were mostly sunk more than half of the total depth required, but temporarily abandoned.

On the section of 6¼ miles of tunnel under construction the shafts are 24 in number, being spaced about a quarter of a mile apart with an average depth of some 175 ft., the deepest being 300 ft. and the shallowest 65 ft. deep.

The city of Mexico is situated on the central table-land of the Republic at an elevation of some 7 500 ft. above sea-level and at the extremity of a large flat valley surrounded by mountains, through which there is practically no exit for the water falling in this basin. The city is at present drained into Lake Texcoco, one of the lakes surrounding the city, but there is little fall even in the dry season, and in the wet season the waters frequently back up in the sewers and cause inundations in the streets. Various palliative measures, such as pumping at the outfall of the sewers, etc., have been adopted which have somewhat modified the evils, but nothing but the completion of the tunnel at present under construction, coupled with proper sewering of the city, can ever cure the existing evils and make the valley and the city what they should be, with the delightful climate and situation. The object of the works is therefore two-fold, to control the water in the lakes and in the valley, getting rid of any injurious surplus, and to afford an outlet for the storm waters and sewage of the city proper.

The works consist of a canal some 35 km. long, starting from the city gates, and a tunnel with a length of some 10 km. The canal varies in depth from 5.5 m. to 20.5 m. at the junction with the tunnel.

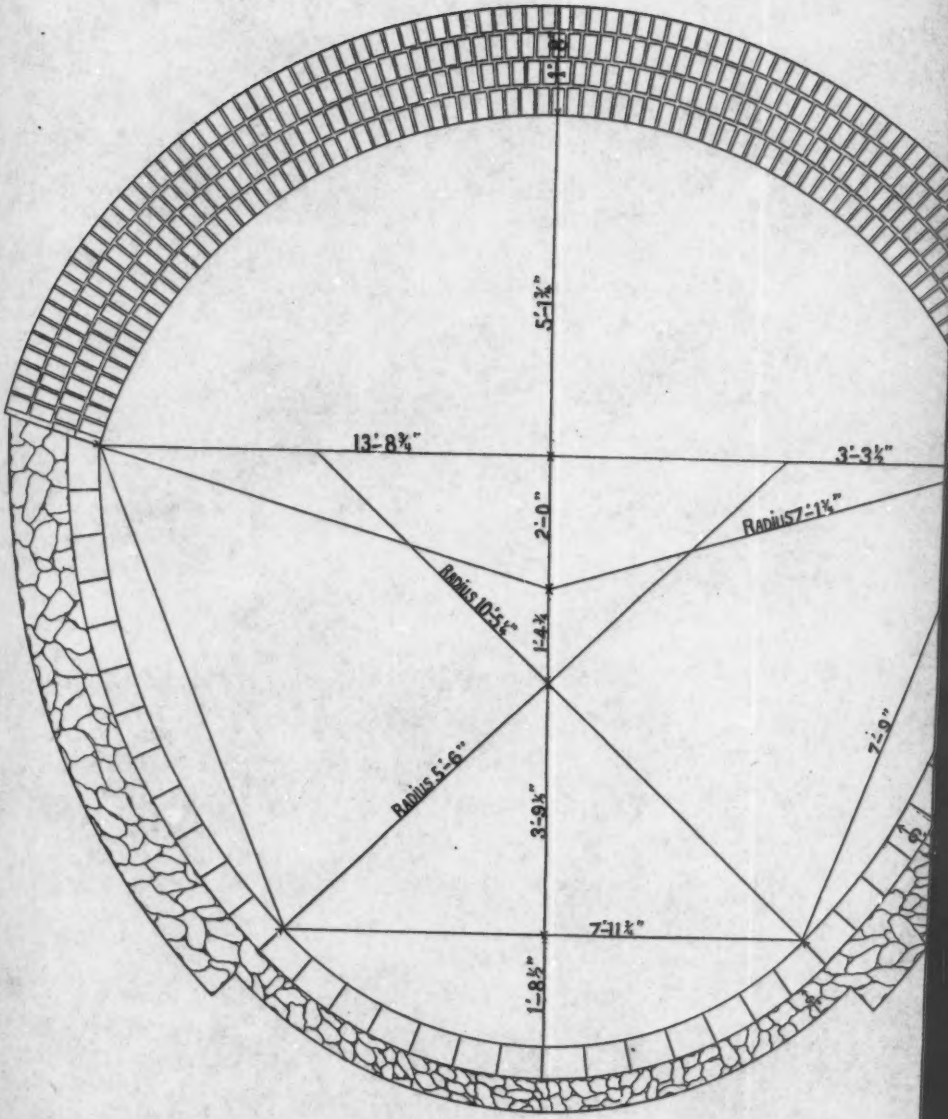
In March, 1892, the Drainage Commission decided to concentrate, as far as possible, the pumping machinery at the shafts at the northern or open end of the tunnel, and to devote special attention to a vigorous prosecution of the bottom heading with a view to connecting the various shafts as speedily as possible, and of so affording an outlet for the waters through the open end of the tunnel. As time was not such an important element in the contract, and, further, as a great many of the most heavily watered shafts had now, in spite of great difficulties, been sunk and the tunnel in part built from them, this scheme promised to give the best and most economical results. At the date of this change the back of the difficulties had been broken, the tunnel was in active construction at numerous points, and the organization perfect in every respect.

This change in the plan of working was largely due to Mr. J.

Limantour, President of the Drainage Board (now Minister of Finance), who insisted especially on a more vigorous prosecution of the bottom heading at any cost, although at that time the results obtained in driving the heading did not appear likely to reach anything like those ultimately obtained. When this plan was commenced there was about 1½ miles of the tunnel completed at the open end, which afforded an excellent outlet for the water. While the bottom heading was being pushed from one shaft to another, no other work was, as a rule, attempted in the same run of ground, as it was found that it delayed more or less the progress of the heading. As soon as two shafts were connected, tunneling could be commenced at once between them, providing care was taken not to block the water and so stop work in the heading which was being driven ahead to connect with the next shaft to the south. In order to make speedy tunnel progress, it was necessary to obtain as many working faces as possible by the construction of break-ups or intermediate sections of tunnel between the shafts, break-ups having been used by the contractors previously with great success; and so, as soon as a tunnel was started from the two shafts, some convenient spot in the heading between the shafts would be selected and break-ups made through the heading and a length of tunnel opened, by which means two more faces were obtained to work from. The number of these break-ups depended on circumstances, on the nature of ground, etc.; for instance, between Shafts Nos. 14 and 13, one break-up was used; between Nos. 14 and 15, two break-ups, and between Nos. 15 and 16, three break-ups; it was found, however, that two was the best number for convenient working. When the deepest shaft (having a total depth of 300 ft.) was in operation, there were, in working one regular tunnel face towards the north or open end, and one to the south, three break-ups, and then the regular face of Shaft No. 16, north; the faces were divided between the two shafts, and No. 17 had, therefore, to deal with one face to the north and one face to the south, and also a break-up and a half, or three faces, or in all, five faces, a large number for a shaft of such depth, and of such a small section.

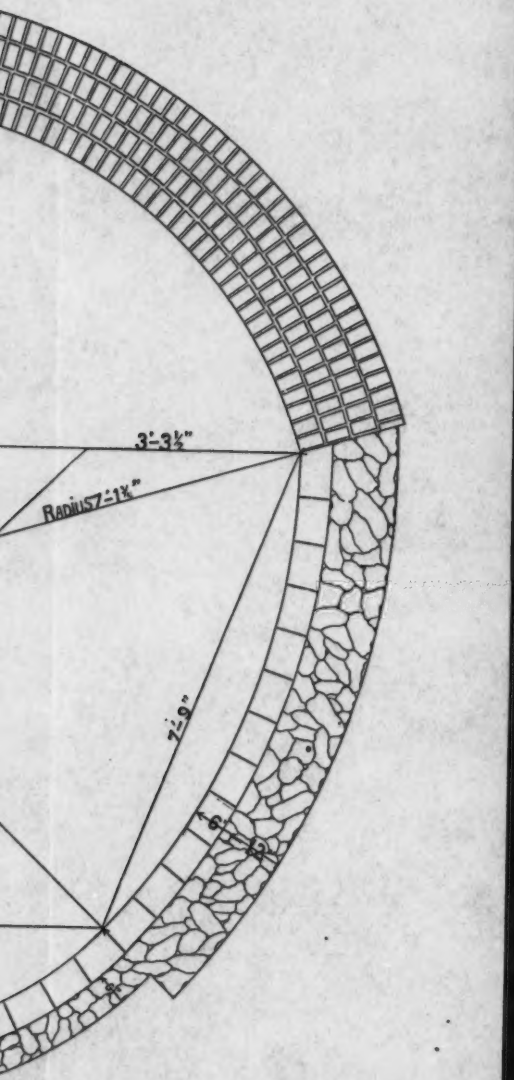
By means of these break-ups the progress of the tunnel was very materially increased, as each face would average 60 to 90 ft. per month, making it possible to join the tunnel between two shafts in about three months; where the double-length system (mentioned later) was employed, better progress was made.

PLATE
TRANS. AM. SOC.
VOL. XXXII,
CAMPBELL AND ABBOT ON



CAMPI

PLATE XX.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 725.
CAMPBELL AND ABBOT ON TEQUIXQUIAC TUNNEL.



Not only was work carried on from the open end and in shafts nearest to it, but also, at isolated points where water could be easily dealt with, both tunnel and heading were vigorously prosecuted.

The choice of points to be worked, and the general scheme of work, the decision as to where heading only was to be driven and no tunnel constructed, etc., were matters of considerable study in order to obtain the best results with the smallest possible expenditure; but it is unnecessary to go into this question here. It suffices to say that the Government placed itself more or less in the hands of the contractors in these matters, and co-operated with them most heartily in all their plans.

It is purposed in this paper to draw attention to the more special points in connection with the construction of this tunnel, not going into the whole detail of construction, as this would lengthen the paper unnecessarily, and only be a repetition of the facts known in connection with other tunnels.

General Description of the Tunnel.—The tunnel section, grades, etc., are those determined by the Government Engineers, under the direction of the Chief Engineer, Mr. Espinosa, as are also the materials employed, etc., the whole work being carried out according to the Government specification.

The tunnel section, as shown on Plate XX, is more or less egg-shaped, but flattened at top and bottom, the chord of the arc being approximately of the same length as the height; the chord is 13 ft. 9 ins., while the height is 14 ft. The flow is calculated to rise as high as the spring of the arch, giving a depth of water of 9 ft. The velocity is calculated at about 4½ ft. per second; discharge about 200 000 galls. per minute, the grade being .72 m. per 1 000 m., or 1 ft. in 1 388.88 ft. The shape of the tunnel is open to a certain amount of criticism, and, as far as the builders were concerned, caused great inconvenience on account of the heavy dish of the invert, increasing the depth of the dead water and greatly cramping operations generally.

The arch consists of four concentric rings of bricks laid with their length horizontal to the arch in the same direction as the axis of the tunnel, and without bond between rings except now and then. The size of the brick is 4⅛ ins. by 9⅛ ins. by 2⅜ ins.; the depth of the arch, 20 ins., allowing for joints. The local tezontle mortar is used in ordinary ground, cement mortar only being used in special cases.

The invert and side walls are constructed of artificial blocks, with a backing of volcanic stone rubble masonry. The thickness of the side walls, including backing, is 18 ins., while the invert or dish has a total thickness of 1 ft. The size of the blocks is 1 ft. 3¾ ins. by 7⅞ ins. by 5⅞ ins., and they are made of 1 part of Portland cement to 3 of sand, rammed in moulds and finished by hand labor.

The mortar with which the side walls and invert are constructed is made of 1 part of lime, 1 part of sand, and 1 part of tezontle.

When cement mortar is used, it is usually made of 1 part of cement to 3 of sand.

Materials used in Construction.—Bricks.—The bricks, made by the contractors on the spot, are required to stand a pressure of about 900 lbs. per square inch.

Blocks.—The blocks used in the invert and side walls are made of 1 part of cement and 3 of sand, as previously mentioned. The cement and sand are first carefully mixed together, usually in a hand rotary machine, and this mixture, after being dampened, is rammed by hand in moulds the size and shape of the block, care being taken that the layers are not too thick, and only sufficient mixture being put in the moulds at each ramming to make a thin layer; iron rammers are used and every effort is used to make the mass as homogeneous as possible. The faces of the block are made to conform to the arc of the side walls and the invert, moulds with templates of the required form being used for the various blocks, while the blocks for the top of the side walls are made with their upper face inclined at an angle equal to that formed by the radius of the arch so as to make an effective key with the arch above.

The blocks, like the bricks, are capable of resisting a pressure of some 900 lbs. to the square inch.

Mortar.—This for the bulk of the work, consists of a mixture of lime, sand and tezontle in equal parts, and only in extraordinary cases is cement used. The lime is of an exceptionally good quality and strongly hydraulic. The limestone is quarried in the immediate neighborhood, and the tezontle, which is a highly ferruginous volcanic tufa; is also obtained close at hand and is ground in the mortar pans to an impalpable powder before being used. The sand is good and clean and fairly sharp. The quicklime weighs about 40 lbs. per cubic foot.

All the mortar is mixed in pans. The lime and sand are first mixed

dry, the tezontle added and the whole then shoveled into the pans and made into mortar. This mortar, when mixed, owing to its being so slow setting, can be allowed to remain some little time before using without injury to its qualities.

Cement Mortar.—This mortar is made of 1 part of Portland cement to 3 of sand, and is usually mixed by hand. It is only used where called for by Government engineers in view of special pressure on arch and side walls. In wet places it was found very hard to prevent the cement mortar from washing away entirely, and an expedient used with fair success, although a questionable method was that of mixing a little clay with the mortar, to give it consistency.

Stone.—The backing is constructed of volcanic or igneous rock found in the neighborhood, laid as rough rubble. This rock is a very hard and heavy class of porphyry, generally with rounded edges, not occurring in pieces larger than 4 cu. ft., and weighing about 160 to 170 lbs. to the cubic foot.

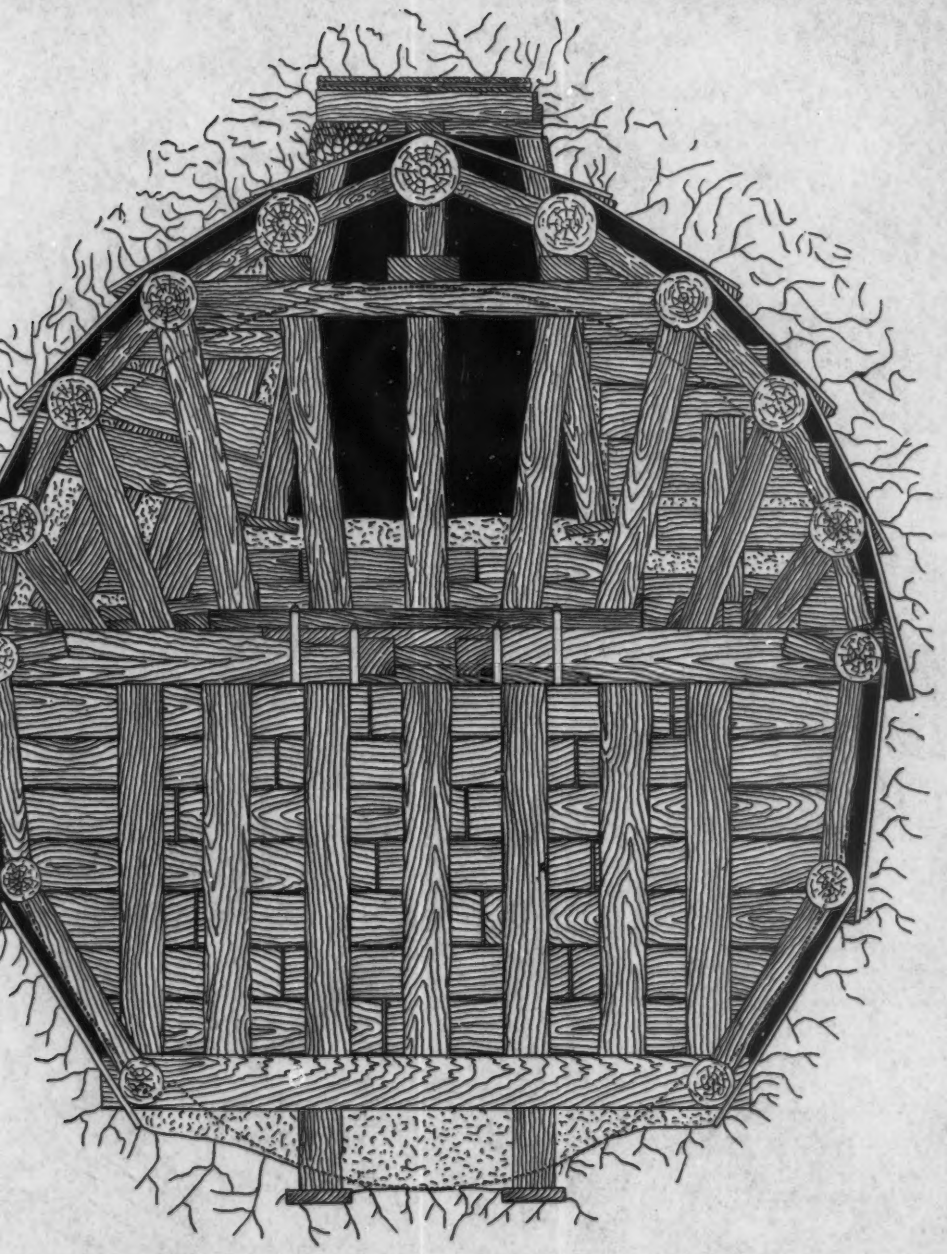
The quantity of materials actually consumed per lineal yard of tunnel is as follows:

1 800 bricks, including packing.
94 blocks.
3 cu. yds. of tezontle and lime mortar.
One-fourth barrel of Portland cement.
70 cu. ft. of volcanic stone.

Nature of Ground.—The ground through which the tunnel is driven is of a very unusual character. There are no regular strata, and therefore nothing to depend upon in the way of indications while sinking the shafts in regard to the nature of the ground likely to be encountered. The whole district is of volcanic origin. The hills bordering this portion of the valley of Mexico appear to have been originally formed from materials erupted from adjacent volcanoes, these materials having been deposited under water, probably in great inland salt lakes. Subsequent upheavals have caused the present configuration of the ground and resulted in a confused mass of sand, mud, tepetate of various degrees of hardness, masses of porphyry and some soapstone, with no regularity of stratification. The tepetate, a local name largely used in Mexico, is a term generally applied to a species of sandstone mixed with lime in various proportions. This tepetate takes all forms, from stone of an oolitic character, in which sand and lime

occur in large rounded grains to a stone consisting of a compact mixture of sand and lime with every degree of hardness. In two instances the tepetate proved so hard that it was possible to take out a 24-ft. length without a stick of timber in it. But the amount of ground encountered of this quality has not been more than 1% of the whole. The greater part of the ground met with consisted of a soft but fairly compact material, which, on being exposed to the air, immediately crumbled and swelled, thus throwing, in some instances, very great weight on the timber. Probably 60% of the tunnel ground was composed of this, the rest consisting of sand, compact and running, and sand with boulders, some of it very heavy and some comparatively light ground. The boulders of porphyry were all water worn and rounded, in some cases cemented together by the sand, in other cases quite loose, but always accompanied with large quantities of water. Water was also always met with in large quantities in the hard tepetate and the sandy formations, while the soapstone formations were as a rule comparatively dry. These formations did not succeed each other in regular sequence, but were all mixed up together in a most inexplicable fashion, so that it was impossible to foresee what ground would be encountered from week to week, almost from day to day. In addition to these peculiarities potholes were frequently struck from which water would flow out with great force, bringing dirt, mud and stone, with it On two or three occasions these bursts of water were so large as to temporarily drown out a pit, and in one case such a tremendous rush of water, mud and stones was encountered in a face 700 ft. from the pit that it tore up 600 ft. of track, twisting up the rails, etc., and filling the tunnel 4 ft. deep with sand, and washing out the miners from the heading. These potholes were, however, always exhausted after a short period of pumping.

In the soapstone formations which were usually fairly dry, if anything happened to cause a fall of the ground on account of bad timbering, it was immediately followed by water which made the ground excessively heavy. The water in the hard tepetate formation has at times been so strong that in some lengths it has been almost impossible to get the workmen to work, owing to their inability to see or use their tools on account of the steady downpour of water, which came through the tepetate as if from a shower bath under very heavy pressure. In these cases shifts had to be cut down sometimes to four hours.



CROSS-SECTION IN HEAVY GROUND REQUIRING FULL SET OF TIMBER.

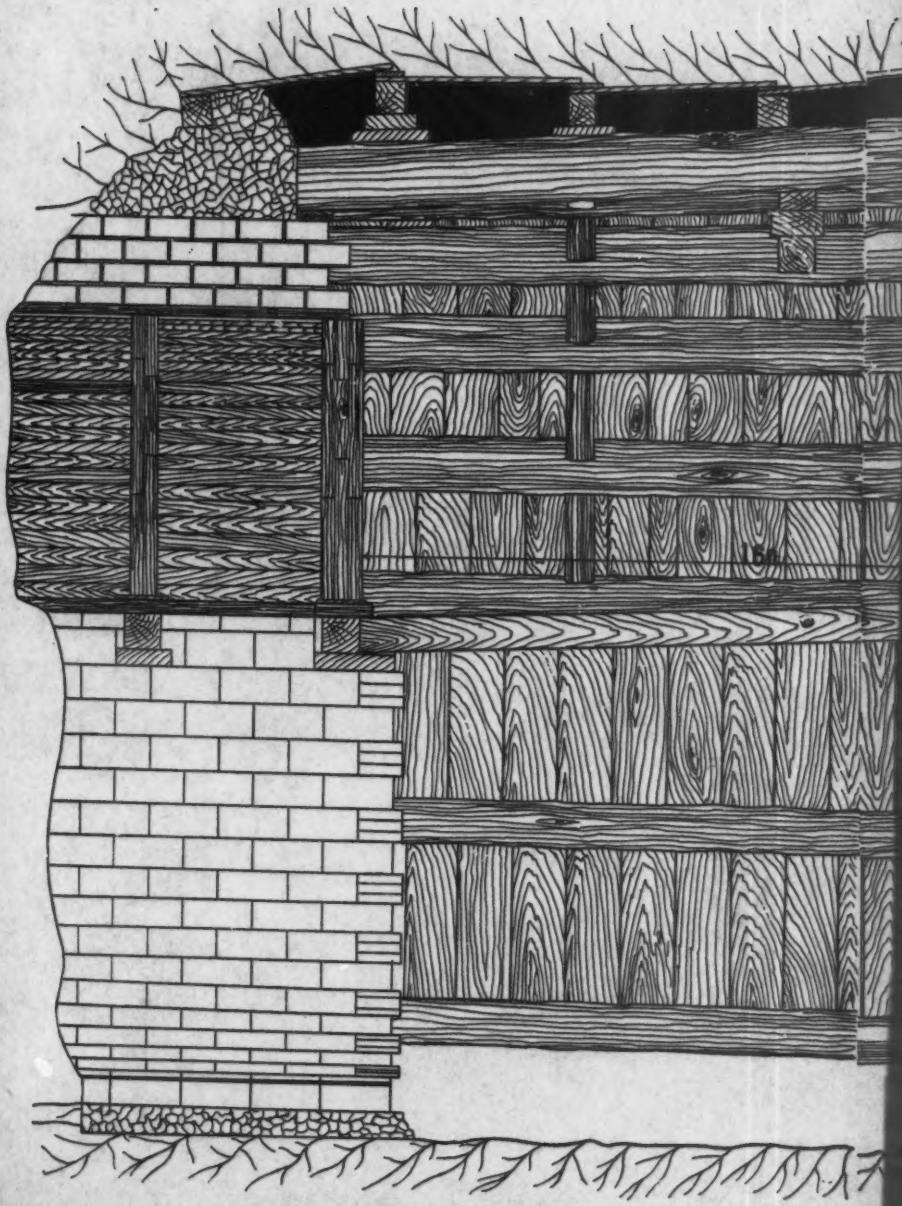
Timbering in Tunnel.—As will be gathered from the description of ground encountered, it is necessary as a rule to take out the ground with what is known in tunnel parlance as a full set of timber (of course this is a very elastic term in one way, as it can be extended to embrace any amount of timber), but as a rule it does not mean less than two sills and generally means that all ground is held up and sustained by timber and none of it left to stand alone. The amount of timber usually employed has been as follows: nine bars, three of them drawing bars, stump props and nipper sill with props, large scarfed sill with props and bottom sill, judkins, stretchers, liners, cockroost and in a few instances rakers. The lengths taken out usually average 14 ft. of finished work, the sill being squared all the way from 15 ft. 6 ins. to 17 ft. The best progress up to quite recently, made in full timbered lengths was five lengths of completed tunnel per month or about 70 ft., and the best average in soft ground per month, four lengths or 56 ft. The local workmen were at first unable to attend to the timbering without being closely watched by English soft-ground miners night and day, and although they after a time picked up the general method they were for a long time so careless that it was unsafe to leave them alone without constant and careful supervision in the heavy lengths, as they could not at first be brought to see the importance of such minor points as packing, feathering, catching head trees on crown bar, stretching side trees, etc., all of which little omissions increase the weight of ground. With time, however, they have improved wonderfully and are now remarkably quick and handy. In the hard tepetate only five bars and a sill are used as a rule, the bars being taking out bars, but the tepetate in these cases was often so hard in the invert that as good progress could not be made as in the softer ground, requiring more timber. Dynamite could only be used sparingly in the hard ground on account of the timber overhead, and consequently the ground came out very slowly, as at first the local workmen did not show great aptitude in using the pick. Work was carried out to the best advantage in regular lengths in the soft soapstone ground and in the soft compact ground already mentioned, as this as a rule could be taken out with one sill and nine bars, the crown and thirds being as a rule drawing bars. Crown and third bars were usually given from 1 ft. to 18 ins. drop, so as to allow ample space for settlement if ground turned out very heavy. It may perhaps be well to mention that drawing bars

are used in heavy ground, and taking-out (or striking) bars in good ground. The names fairly express the difference between the two; the drawing bars are always placed so as to be entirely outside the work, the striking bars come on the second and third ring of brick work and are struck as the arch comes up to them.

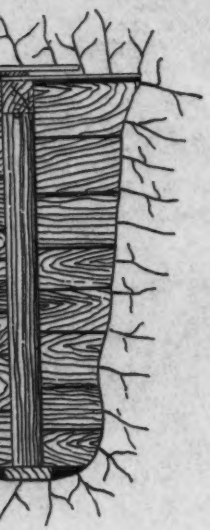
The best progress of all until quite recently was made by means of working double lengths. This system of working double lengths was employed where the ground consisted of tepetate that required timbering merely to keep the ground in place, and where, if the ground was kept in place, it did not suffer any movement that would be likely to throw extraordinary weight on the bars. It was necessary for the use of this system that a bottom heading should have been previously driven, the necessity for which will appear later.

In ground of the character just described a length usually required nine bars and a top sill and sometimes liners, judkins and stretchers being also used, but no cockroosts, the bars being all taking-out bars, and one crown bar and two crown bars being used alternately. The top heading was always driven further ahead than customary, to admit of this system which really had for its only requirement the putting up of bars in two lengths at a time. When working a single length, after the length has been lined up, if the bars are drawing bars, they are pulled ahead, and if they are striking or taking-out bars, they are taken out as the arch is built up; but in either event no operations are commenced for putting up the bars in the following length until the completion of the single length under construction. With the double-length system, when one length is keyed up, the next length probably has seven bars and the sill in, and the top heading is being prepared for the crown bars in the next immediately ensuing length, the said bars coming from the length just keyed up.

When using the double-length system, by the time a length is excavated requiring, say, one crown bar, two thirds, two fifths, two sevenths, and is ready for the masons, there will be in position in the top heading for the new length on each side of the crown bar two other crown bars whose ends can be seen projecting in the diagram and the position of which explains the necessity for using one and two crown bars alternately, as the bars have to be sandwiched in between each other. The two crown bars in the top heading are propped on the sill of the length the masons are about to enter, and at their extreme end



XXII.
C. CIV. ENGRS.
, No. 725.
TEQUIXQUIAC TUNNEL.



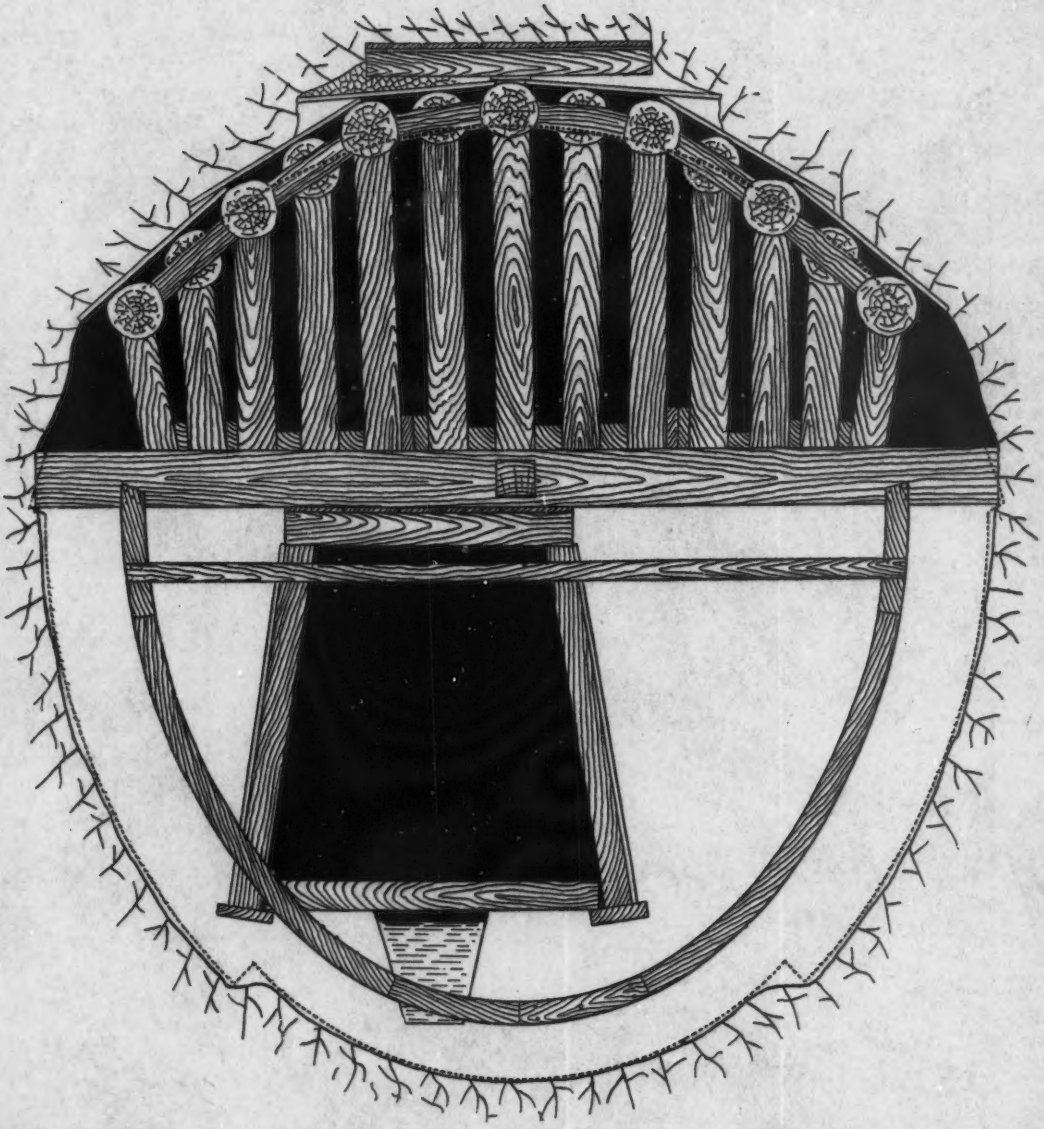
rest on short stump props. If they are not sandwiched in between the crown bars and the third bars of the length the masons are about to enter, they would not be able to be propped on the sill. These two crown bars come from the finished length immediately behind the length about to be lined, and are propped high enough to clear two rings of the arch about to be constructed in the excavated length. When the masons have started work in the excavated length, polling for the fourths is proceeded with in the top heading for the new length; and when the side walls are up in the excavated length, ready for the byats, the fourths are hauled ahead from behind and put in, while the ribs are being set for the arch in excavated length. Directly the arch is started, polling is proceeded with in the new length for the sixths and eighths, a nipper sill and props being at the same time placed in position to catch the bars, and a lining setting being placed in the bottom heading to sustain the nipper sill above. As the arch is finished and keyed, the sixths and eighths are probably in and the main sill also in and propped. The fourths and crowns in the new length are caught on the arch as it comes up, while bar holes are left for the sixths and eighths, so that by the time the length under construction is keyed up, the top heading has been converted into a new length with eight bars and sill in, and the hardest part of the work of excavation finished. The one crown bar from the keyed-up length is now moved ahead into the new top heading, to be sandwiched between the two crown bars, and the operation proceeded with as before, with the exception that in this length seven bars will be used instead of eight, for reasons already given. The drawings (Plates XXIII and XXIV) show very clearly the arrangement of timber in the double-length system.

The necessity for the bottom heading now becomes apparent. While the length with the sill in is being completed, it would be impossible to commence a length ahead of it if it was necessary to take the dirt from excavation in the length ahead through the back length, as it would too seriously interfere with the progress of the work; again, while the masons are on the arch of one length, it would be impossible to take dirt out from the length ahead through the length being lined without interfering with the masons. By the use of the bottom heading however, a separate communication can be made in either length by means of knocking a hole through from the top heading and loading

the coaches underneath. This system of double lengths has been very successful, as much as eight lengths in one face, or 120 ft. of complete tunnel, have been constructed per month. This system has latterly been still further extended with considerably better results as regards speed, as will be referred to later. In using this system, extra care has to be taken and the timbering watched carefully. The bottom heading must have lining settings placed under the nipper sills, and all the settings must be carefully stretched and watched, as there is always a chance of the stump props under the bars pushing through into the bottom heading. Of course this system cannot always be used, as it is not frequent that the ideal material, just soft enough not to require the use of explosives, and not hard enough to stand with a small amount of timber, is encountered.

Timbering in Top and Bottom Headings, and use of Headings.—The timbering for top and bottom headings is practically the same; the top heading is driven for the drawing of bars in the construction of ordinary lengths; the bottom heading, by far the more important of the two, is driven for three important reasons: First, the connection of shafts with the open end, as, immediately the said connection is made, the pumping in the shaft connected with can be discontinued, and also for the connection of shafts not in communication with the open end; second, to enable break-ups to be constructed, a point which will be touched on later; and third, to enable the double or treble-length system to be worked in the manner already explained.

The dimensions of the bottom heading are as follows: 6 ft. 6 ins. high; 5 ft. at top, or 4 ft. in the clear; 7 ft. wide at bottom, or 6 ft. in the clear. In good ground it was possible to excavate 6 or 8 ft. ahead, putting in settings as heading advanced. In bad ground it was necessary to use the ordinary methods of driving polling boards ahead, working temporary head trees, etc. The majority of the heading, however, was driven through fair ground, which allowed of excavating 6 or 8 ft. ahead, and putting in settings as heading advanced. The side trees, which were 6 ins. by 7 ins. by 6 ft. 6 ins., were cut to bevel at a saw mill, so that, when they were fitted snug to a head tree of 7 ins. by 7 ins. by 5 ft., they would then have the required batter. In good ground, polling boards of 1 in. by 12 ins. by 5 ft. were used; in bad ground, polling boards of 1 in. by 1 ft. by 3 ft. 6 in, or 1½ ins. by 1 ft. by 3 ft. 6 in.



CROSS-SECTION IN LIGHT GROUND, SHOWING SYSTEM OF DOUBLE LENGTHS.

In good ground, settings were about 4 ft. apart, with sides and top lined with 5-ft. boards, lining settings being put in between each original setting as the heading progressed. In the bad ground, where the settings were only 3 ft. apart, lining settings were also used. As a rule, the bottom heading was driven 2 ft. above the invert of the tunnel so as to keep the road above the dead water of the tunnel. As already mentioned, this heading was required for purposes of drainage from one shaft to another; it was therefore necessary to cut a grip or drain in this heading 2 ft. deep, as otherwise, on account of the grade, the water in the shaft just communicated with would be some 2 ft. too deep, when the tunnel began to be constructed. The excavation of the grip necessitated the use of good sleepers under the road, to prevent it from falling into the grip, and these sleepers were made at the same time to serve the purpose of stretchers at the bottom of the side trees, between whose sides they were wedged.

Progress in Heading.—The average daily progress in bottom heading for the year ending the 1st of June, 1893, was about $5\frac{1}{2}$ m., the daily progress ranging from 4 to 6 m., and on a few occasions being as high as 7 m. Prior to June, 1892, the average daily progress in heading was only about $1\frac{1}{2}$ m.; and whereas, the former progress compares favorably with work done under similar conditions anywhere, the latter is far from doing so. The slow progress made at first with heading was due to a variety of causes, among others the following:

First.—To attention being mainly devoted to working from each shaft, using pumping machinery for dealing with the water, on account of the short time allowed for the execution of the work.

Second.—To the inexperience of all concerned in driving this class of heading; the ordinary soft-ground English miner proving useless directly he was put in a heading where the ground was fairly good and rapid progress—not timber—required, and the local labor proving very inefficient from want of previous training, when it came to hard pick work and constant application.

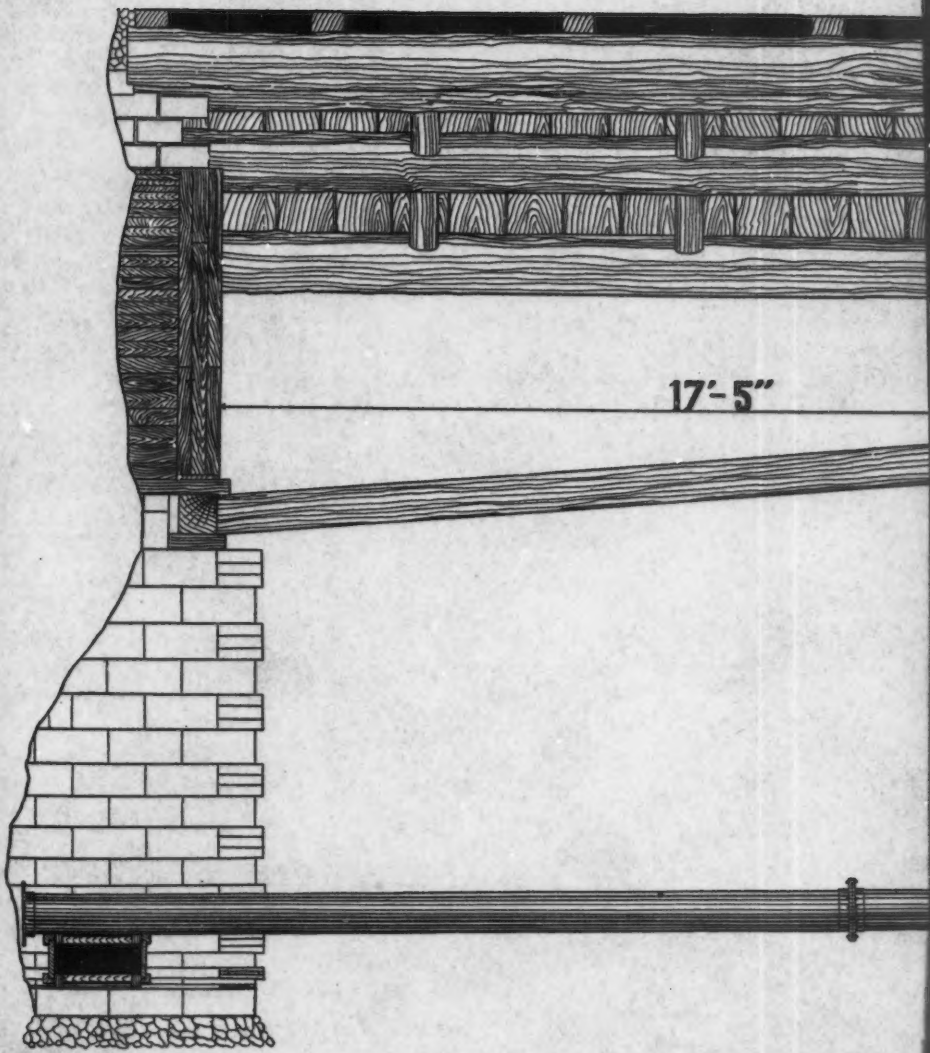
Third.—To the difficulty caused by the heading being originally driven in the center, rendering it possible to use only one road in the tunnel, so that, when the tunnel and heading were being constructed at the same point, preference had to be given to the tunnel traffic to the entire detriment of the heading traffic.

Fourth.—To a short-sighted unwillingness to pay high-enough prices for driving of heading.

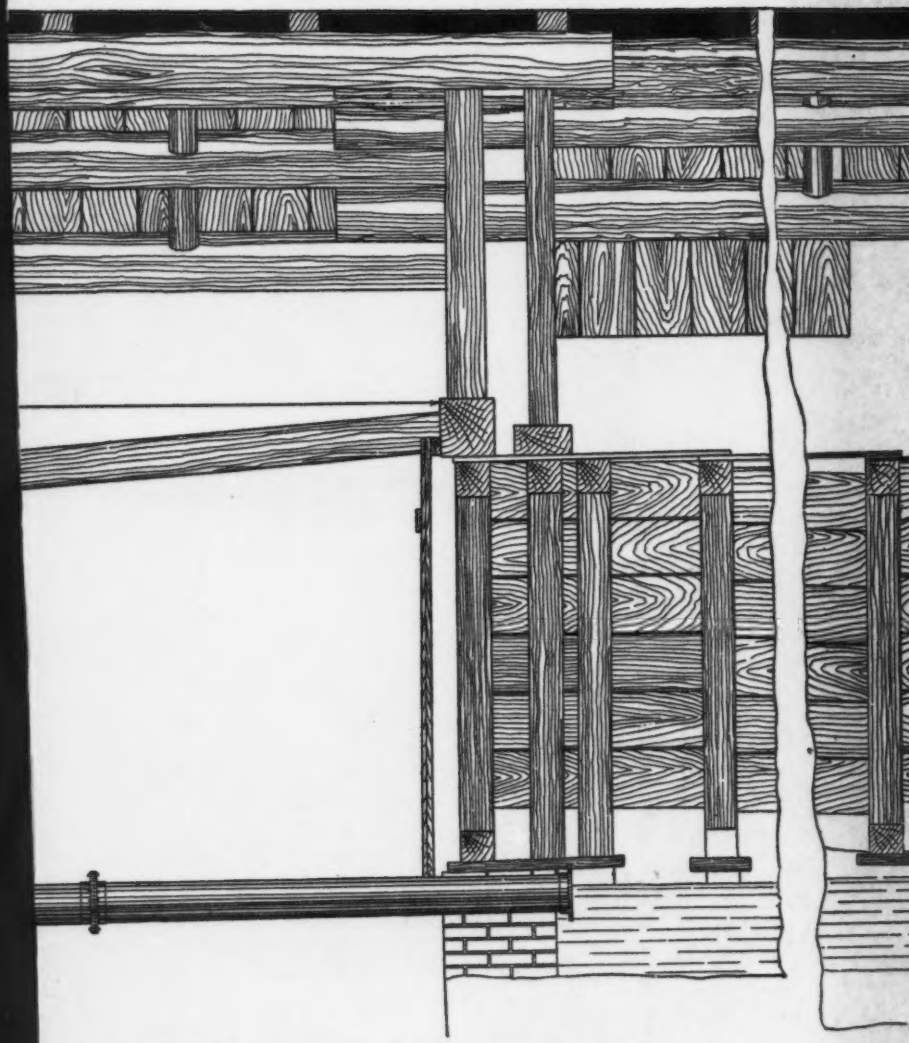
Fifth.—To the want of sufficiently careful organization and of the minute attention to details necessary, no arrangement having been possible at first, or, at least, made, for the working of regular shifts with carefully picked men specially adapted to the work. Later on, when a special feature was made of driving bottom heading, very careful attention was given to the matter, and the difficulties and faults mentioned and others were gradually overcome and corrected.

The extraordinary speed obtained latterly, higher undoubtedly than in any similar work, would appear to call for some other explanation than that given, but can only be attributed to the following additional reasons: First and most important, constant attention and personal supervision night and day, not only by gangers, foreman, etc., but also by the agent and engineering staff, measurements being taken every morning, heavy fines imposed for delays, and every inducement given to push on the work. Attention was given to the smallest details in connection with the work, the track in the tunnel was most carefully laid, the provision of cars in proper number, and the winding arrangements and handling of material underground and at surface, studied to ensure no hitch or delay of any kind. Another reason was (as already mentioned) that, as more of a feature was made of the heading, it became possible to dispense, in a measure, with pumping expenses for the purpose of connection of shafts, and a higher price could be paid for the labor employed in the heading, which was far more than compensated for by the advance made. When, after considerable opposition, eight-hour shifts were introduced instead of ten-hour, the progress went up to $5\frac{1}{2}$ m. per day very quickly. It must be borne in mind that the local labor was at first comparatively ignorant, both as regards tunnel and heading work, and had to be taught and trained; it proved remarkably quick and imitative, and under good direction and with proper tact and patience is capable of almost anything.

In working eight-hour shifts the miners were kept constantly in the face and not allowed to leave until the expiration of their time. There were usually two or three miners in the face, with from 6 to 10 men, varying with the distance, at the cars removing dirt, with a native foreman to supervise generally. All these men were changed every

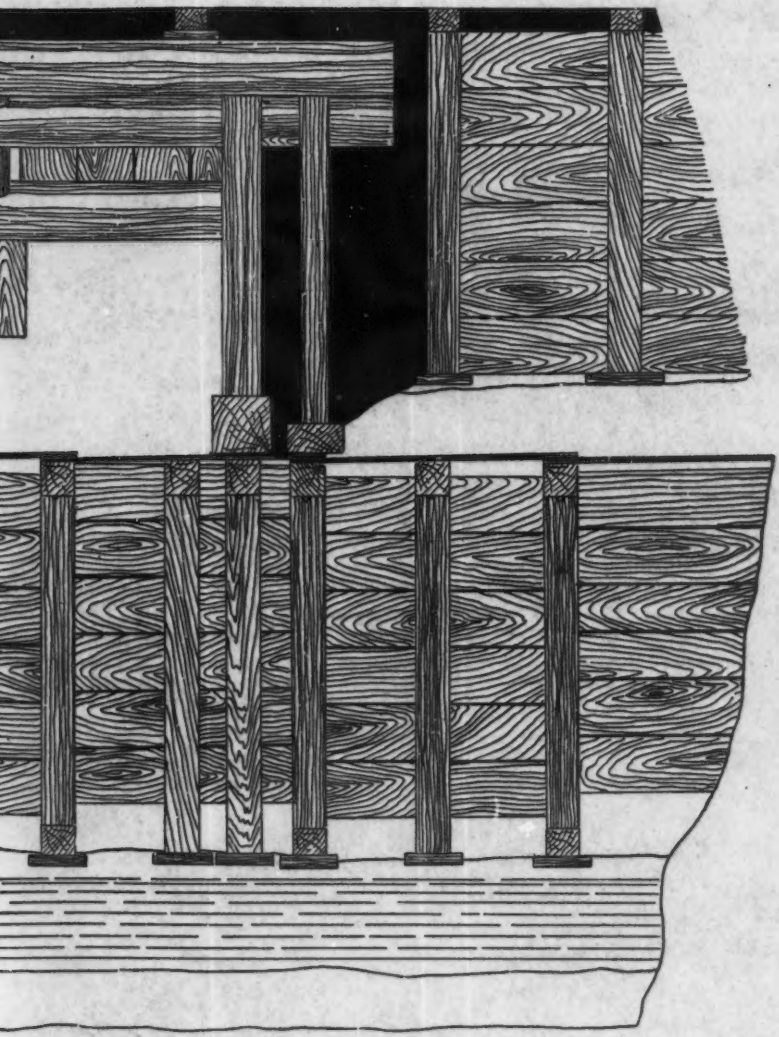


SECTI



SECTION IN LIGHT GROUND, SHOWING SYSTEM OF DOUBLE LENGTHS.

PLATE XXIV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 725.
CAMPBELL AND ABBOT ON TEQUIXQUIAC TUNNEL.



eight hours; in addition there was usually an English or American foreman to attend to putting in settings in line and level, and to the receiving and carrying out instructions, etc. This foreman was paid a shift and a half for each 24 hours, and was supposed to be there when needed. In addition to the men in the heading there was a gang of about six men behind cutting grip, laying road, putting in intermediate settings, etc., and also a man at pit bottom to attend to ringing up of cages, etc., above; there were from two to six men at coaches at pit mouth, and one man to attend to landing of coaches from the cages.

When later heading was going well and organization complete, the task every 24 hours was set at 6 m., and the subcontractor fined if the task was not completed; of course, where there were special reasons, such as exceptionally heavy ground, the task was not insisted upon. Dynamite was as a rule required in quantities of from 2 to 3 lbs. per lineal meter, or about 1 lb. per cubic meter.

The heading was all carried out by subcontract at so much per meter, the work being left to specially selected local subcontractors capable of pushing and controlling the men.

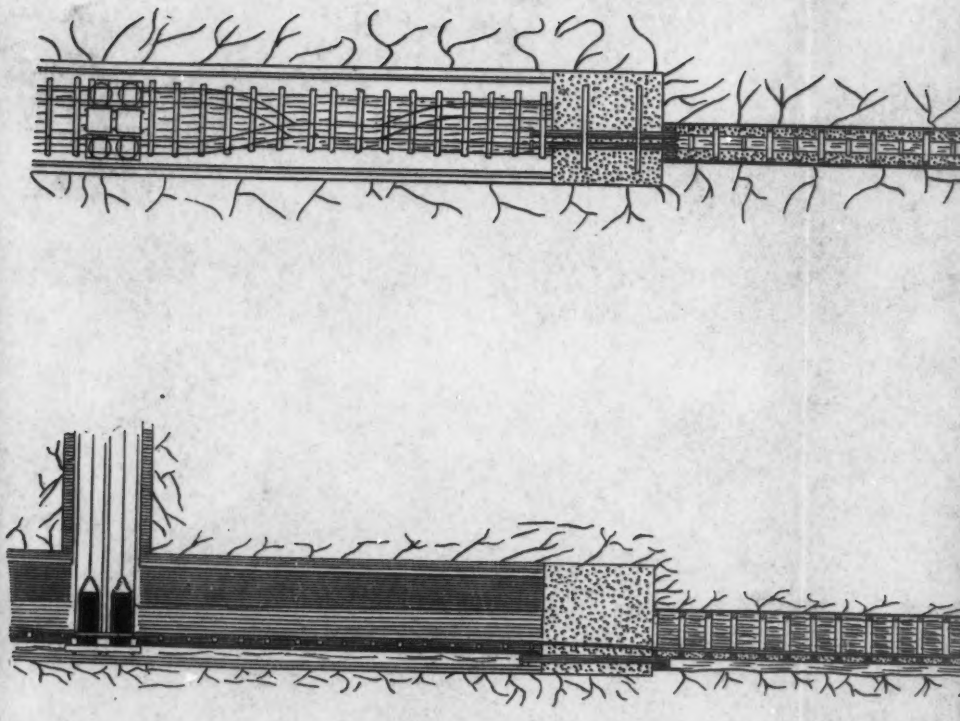
Lining of Lengths.—Immediately a length of ground was excavated for tunnel construction, a frame (shown on Plate XXIII), the exact shape of the invert, was set at the leading end of the excavation to the correct level and alignment of the tunnel, lines being stretched between this frame (which is notched at the level of each course of artificial blocks) and the blocks in the finished tunnel in the length behind. The masons then commenced to lay the backing, and on top of it the blocks, lining up with the lines until the invert and side walls were completed, the special blocks referred to as having their upper side parallel with the radius of the arch being laid last. Holes were left in the last course but one, at intervals of 3 ft. 6 ins., to receive the byats, the byats were footed on wooden foot blocks about 2 ins. thick laid over the cement blocks, the foot blocks forming a sort of pad in the cement blocks, as otherwise it was found that the weight of the arch would often crush the sharp edges of the byats into the blocks, causing them to crack and necessitating their renewal. On the byats being placed in position, 3-in. planks were laid along their ends parallel to the axis of the tunnel, and on these the ribs are set and wedged up to the required level. The ribs are made of two thicknesses of 2-in. plank bolted together and cut in sections, to form the required circle; the leading

rib is always made of three thicknesses, to sustain the extra pressure it frequently receives, owing to the crown bars resting on it. Laggings 2 ins. by 4 ins. by 16 ft., more or less, are then placed on the ribs, to receive the brick work and continued to be placed as the arch is carried up.

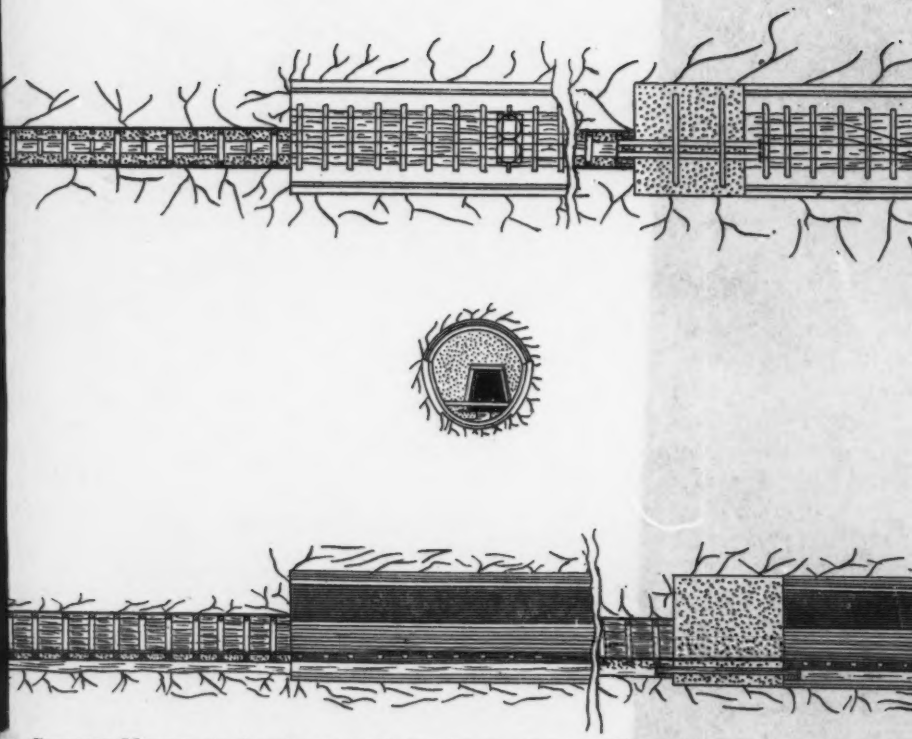
When the arch has been carried up on both sides till the two sections are only 1 ft. 6 ins. apart, it is necessary in ordinary practice for the force of masons to stop, as only one man can work conveniently and finish the arch, or the keying up. In ordinary practice it is usual to use pieces of lagging of short length that will reach from one rib to another instead of using laggings of the full length as before, thus enabling the mason to get in between the ribs and key from one to another. Here block laggings are used when the arch is stopped as mentioned above the key. These block laggings are 18 ins. long and about 1 ft. wide, with grooves cut in the upper sides, and, instead of being placed like the others parallel with the axis of the tunnel, they are placed at right angles to it. By using these laggings the mason can key and pack much more satisfactorily, as when one block lagging is placed in position, it being only 1 ft. wide, he is able to work in and over to much better advantage than if he was working on the older system and was obliged to stretch from one rib to another, a distance of 3 ft. 6 ins.

The question of packing above the arch—a most important one—was one of great difficulty at first, owing to the difficulty of persuading the local workmen to execute it properly. Where striking or taking-out bars were used it was easier, as it could be done simultaneously with the construction of the arch; but where drawing bars were used, and a feather or pillow of brick had to be constructed on each side of the crown bar all along the arch, to sustain the polling boards when the crown and third bars were struck, it was a matter of greater difficulty.

The average number of men employed at one time in a length is about eight, including the operations of excavating, lining, etc., the least number at the commencement of opening out top heading being four, and the greatest number, while lining arch, about fourteen. At the commencement, as already mentioned, while opening out the top heading, some four men are employed, and as the ground opens out, the number goes up to six and finally to eight men, while excava-

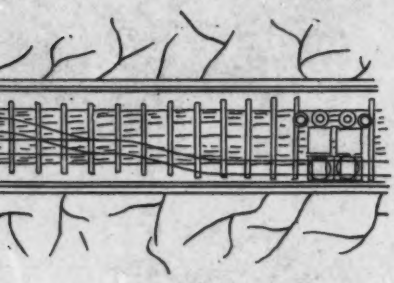


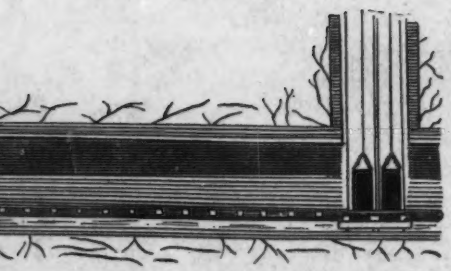
Shaft-to-Shaft Ground Plan, Showing Met



N, Showing Method of Alignment of Road, Arrangement of Headings, etc.

PLATE XXV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 725.
CAMPBELL AND ABBOT ON TEQUIXQUIAC TUNNEL.





ting the invert. When the masons go in, about six start at first, with a helper to each, the number of masons on side walls and arch increasing finally to eight, with six helpers, which number drops down to two on the keying of the arch; this, of course, does not include foremen, inspectors, and men at the coaches, the latter varying from three to six pairs according to the rapidity with which the dirt is excavated and the material used.

The excavation and lining of lengths is all done by subcontract at so much per meter, prices varying according to nature of ground, quantity of water, distance from shaft, etc. In fact, all work, both at the surface and underground, is done by subcontract as far as possible, the results obtained being far more satisfactory than when paying day wages.

Roads in Tunnel.—In arranging the road two requirements had to be considered: First, the necessity of having under the road in the invert sufficient space for an ample channel, to carry away all water that might be encountered without danger of flooding the road; second, the necessity of having the road sufficiently low, to allow of tunnel coaches passing under byats set in the side walls, to support the ribs for construction of the arch. The position of the roads is clearly shown on Plate XXV.

For the track through the completed tunnel a 9-ft. sleeper met all requirements and gave an available width of about 8 ft. for the road, and allowed good arrangement of tracks. Driving the bottom heading in the center of the tunnel, as was done at first, compelled the road to be laid in the center of the tunnel, and, as all the traffic of any break-ups that might be in course of construction ran over this road, it became necessary to put in sidings at all faces in construction, so that if building materials were being used at one face, they could be switched on to a siding, and so leave the main track free for the general movement of dirt, etc. Putting the road in the center with a gauge of 2 ft., and a car 3 ft. wide, only gave 2-ft. 6-ins. clearance on each side, which was not enough for another track, and it became therefore necessary when break-ups came to be generally worked to adopt some other plan, and the heading was then driven 18 ins. off the center, enabling a main line to be run through the heading from shaft to shaft, and devoted solely to the loading of dirt and preliminary movement of material, a siding being put in at each ordinary work-

ing point from a shaft where cars could be unloaded of material and loaded with dirt without interfering with general traffic. For the break-ups an auxiliary line was used, but instead of points and crossings a system of turn-tables was adopted. When a break-up is started and the preliminary length constructed, a double track is required at once; but as in a length of 15 ft. it was impossible or inconvenient to put in points and crossings available for either face of break-up, a straight parallel track was laid and two turn-tables put down, one on the main line and the other on the new track. By this means every facility for moving from one track to the other was given and as soon as bricks, etc., arrived for the break-up length they were immediately run on to the turn-table on the main line and turned on to the parallel line, leaving the main track free, a most important requirement, as when bricklayers were in the break-up, if a second track was not available, all cars moving on the main line would have to wait while the cars carrying material for masons were unloaded. If the lining of lengths in the various faces had proceeded in regular rotation, it might have been possible to arrange the traffic in another manner, and, by sending trains of cars loaded with material to a certain face, and then requiring them to pass on empty to another face, to return full of dirt, avoid some of the difficulties mentioned; but as the chances were that these trains would have to pass through two or three lengths in process of excavation before re-arriving at their destination, and then have to come back to be loaded, it was practically impossible to do so. Considerable attention was devoted to the question of track, as smart and proper handling of material and dirt was indispensable if rapid progress was to be made. The following example from practice will explain this necessity perhaps more forcibly:

Between Shafts Nos. 15 and 16 there were, at one time, three break-ups in construction, besides one face of tunnel in construction to the north of No. 16, one to the south of No. 16, one to the north of No. 15, and one to the south of No. 15; that is to say, 10 faces of tunnel in construction at the same time between two shafts. Ten faces implied, at a moderate estimate, the moving of some 7 000 cu. yds. of dirt, 400 000 bricks, 20 000 cement blocks, 5 000 cu. yds. of stone, and 700 cu. yds. of mortar, besides 50 000 ft., B. M., of lumber, together with rails, tools and other materials, in some 26 working days, and the delivery of much of the material to points distant from the shafts. It was

necessary to distribute the working equally between the two shafts; that is to say, Shaft No. 16 dealt with No. 16 north face, No. 16 south face, north and south faces in break-up No. 1, and north face in break-up No. 2, *i. e.*, five faces. Shaft No. 15 dealt with north and south faces of No. 15, south face in break-up No. 2, and north and south faces in break-up No. 3. The brick, etc., required for a length being lined in north face of break-up No. 2, had to come from Shaft No. 16, through south face of No. 16, north and south faces in break-up No. 1, to get to their destination, with perhaps all these lengths full of men. Five faces meant a monthly construction of, at the very least, 330 ft. of tunnel, or an extraction of about 3 300 cu. yds. of dirt per month, and the provision of 200 000 bricks, 10 000 blocks, 2 500 cu. yds. of stone for backing, and 350 cu. yds. of mortar, not taking into account the movement of timber, men, rails, etc., and as there were only some 26 working days and nights in the month, this implied the handling of one car every two or three minutes. The sleepers used in the track laid through the finished tunnel were about 4 ins. by 8 ins. by 9 ft., spaced some 3 ft. 6 ins. apart. Decauville track, with 12-lb. rails and steel sleepers, was employed, and the rails were also spiked to the wooden sleepers. The steel sleepers could have been dispensed with, but they more than paid for themselves by giving additional stiffness to the road and keeping the track to accurate gauge; the wooden sleepers get sodden, and the spikes would draw unless the track was helped and kept together by the steel sleepers. Most of the points and crossings used were ready riveted, and all that was necessary to move them forward was to take them up bodily, put them on a car and drop them down again where wanted, spiking them in places.

In the bottom heading the track was laid on wooden sleepers 3 ins. by 6 ins. by 6 ft., the sleepers also serving as stretchers, to keep the side trees apart, and, as bridges, to keep the track well above the drainage grip mentioned before. The steel ties were here again very serviceable in stiffening the track and keeping it in gauge.

Drainage in Heading.—The drainage of the tunnel, and more especially of the bottom heading, was a very important point in connection with the successful prosecution of the work, especially at the open end of the tunnel, where work was being done frequently from various shafts at the same time. It will be remembered that regular tunnel faces, break-ups and bottom heading are all being carried on

at the same time, and, where the water had to be drained away through the open end of the tunnel, arrangements had to be made to keep the water-way clear through the work in all its various stages of progress, the principal difficulty being carrying the water through the lengths in which invert was in course of construction. Theoretically, the water ran at the level of the finished tunnel invert, but it was necessary to excavate below this level, to get in the masonry necessary for the construction of the invert, and whatever stream of running water there might be flowing in the tunnel at this particular point had necessarily to be carried across the length of the invert while in construction. At times, when there were as many as three break-ups in addition to two regular faces in work between each pair of shafts, and when two or three shafts were in operation at the same time at the open end of the tunnel, frequently with half the total number of lengths being lined at the same time, the greatest care was necessary in carrying the water over the various lengths of invert in construction, so as to avoid damming back the water more than was absolutely necessary. The water discharged through the open end ran on the finished invert naturally at a depth never less than 12 ins. There was, therefore, this initial amount of dead water to contend with from the beginning; higher up, above one set of break-ups, the water would probably be dammed up a further 6 ins., giving a total depth of dead water of 18 ins, and so on, with the result that, in the face where bottom heading was being pushed forward, the water frequently reached a depth of 2 ft. It was found necessary to drive the bottom heading at a level some 2 ft. above the level of the tunnel invert so as to keep the floor of the heading dry as far as possible. In one case, on approaching Shaft No. 12, the level of the heading had to be raised still higher, on account of the large increase in the amount of water discharged, due to filtration, etc. On heading being communicated between any two shafts, the level of the same, being 2 ft. above the tunnel invert, prevented the water from the shaft just communicated with from flowing away below that level; but seeing that it was indispensable that the water should be allowed to flow away at the level of finished invert in order to render the construction of same possible, a grip was cut in the bottom of the heading 2 ft., either after completion of the heading or carried along simultaneously with it. This grip (as previously explained) required extra timbering as, more

especially where the ground was soft, the sides of the grip were liable to cave in and let the side trees down. A special gang was always employed solely for the purpose of keeping this grip free from mud, dirt, etc., due to material falling from the cars and other reasons, as, should any obstruction occur in the grip, all work above the point choked became seriously inconvenienced, and in some cases might be stopped.

The total discharge of water at the tunnel mouth varied from 1 500 to 3 000 galls. per minute. In excavating an ordinary length and putting in the invert between pumping shafts, water was, as in the case of the open end, always found in the excavation, which was carried as a rule from 15 ins. below the level of the finished invert. On completion of the excavation necessary for the invert masonry, the dead water from the finished tunnel would also immediately run into the excavated length, if means were not taken to keep it out. The entrance of this water was avoided by the use of a dam placed at the end of the last length of constructed tunnel, which backed up the water and prevented it from running into the excavated length. Any water, however, that might be encountered in the actual ground excavated below the invert level or that seeped through had to be pumped over the dam with small hand pumps into the finished tunnel. Working in ground where only shaft faces were in construction, with no break-ups, there was no necessity for carrying the water over the work in construction, but at the open end, as already indicated, it was necessary, also, to deal with the water coming down from above, from all break-ups, faces, etc., and in these cases a dam had to be constructed, not only in the end of the finished tunnel, but in the heading itself, and pipes laid from the dam in the heading to the dam in the tunnel, or *vice versa*, so as to carry the water over the length. At first this did not present any great difficulty, as two 12-in. pipes proved sufficient to carry the water; but later on, when the water largely increased in quantity, the pipes employed had to be largely supplemented, and, latterly, a large launder used, which seriously interfered with the small space available for the masons. When the ground in the heading was soft or of a sandy character, it was found extremely difficult to construct a satisfactory dam. The earth round and under the same would wash away and the water from the heading find its way into the excavated length, filling same and necessitating the reconstruction of the dam, relaying of pipes, etc. This working in of the water, in spite

of all provision, occurred sometimes as often as two or three times in bad ground during the construction of a length, and the difficulties were often further increased by the action of the water washing round the bottom sill props and undermining them. The dam placed in the invert of the finished tunnel was a comparatively simple matter. At first it was constructed of bricks and clay, which were removed on the completion of each length; subsequently, however, a hollow dam was constructed of boards made to fit exactly the shape of the invert. This could be placed in position very speedily and weighted down with clay placed inside; and directly the invert of the next length was finished, it was moved forward before the sleepers were placed in position. This effected a great saving in time and labor. The size of this dam was about 2 ft. 6 ins. high and 8 ft. long, constructed of 1¼-in. planks.

The quantity of water encountered in excavating the ground for the laying of the invert varied very much, it sometimes taking as much as 6 shifts and from 8 to 10 hand pumps to pump out a length before the masonry could be laid, while on several occasions the masonry of the invert had to be laid in some 12 ins. of water.

The plates which accompany the paper show fully the arrangements in connection with the dams, levels at which heading was driven, etc.

Quick Handling of Material Above and Below Ground.—This was a point to which very considerable attention was given, although nothing specially new was used in the way of winding engines, cages, etc. The chief difficulty consisted in proper organization and discipline of local labor, in securing capable drivers for the winding and other engines. The head-gears for the shafts were of the usual type, some 50 ft. high, with two floors, one at the ground-level and the other at about 15 ft. above. The lower floor was used entirely for the cages carrying materials necessary for construction, while the upper was used only for the coaches carrying dirt, etc., extracted. A turn-table was provided for each cage, with a switch and double track to both sides of the shaft, double cages being used in each shaft. At the pit bottom four turn-tables were employed, two to each cage, one on each side, thus affording double means of exit and entrance and communication with the double track in the tunnel. The turn-tables in all cases proved more convenient than switches, where it was possible to employ them.

The arrangement of the turn-tables and of the tracks is also shown in the plates accompanying this paper.

Ventilation.—Ventilation was a point of very considerable importance, especially in pressing on with the heading with all possible speed. Root's blowers, No. 1, 14 ins. by 22 ins., and 30 ins. long, with 8-in. inlet, were used, being worked either by a small separate engine or from the pumping engine. Spiral rolled iron tube, 5 ins. in bore, was used for carrying air into the workings. On any two shafts being communicated, the natural ventilation, if properly looked after, proved to be sufficient. Previous to communication, in some of the headings where a considerable quantity of dynamite had to be employed, and when the distance from the shaft was 800 to 900 ft., the air became so bad as to necessitate the use of two blowers, one being placed at half the distance, exhausting the air, and the other at the face, blowing in air. Considerable difficulty was found in keeping the pipes, joints, etc., in order, as the workmen, if the air was too cold, would frequently plug the pipe; or if at another point the air appeared deficient, would knock a hole in the pipe with a pick and thus satisfy their wants.

Cost of Tunnel.—The cost of the finished tunnel by the present system of working during the last year has averaged from $650 to $700 per meter. It is impossible here to enter into details of the cost, as this subject would fairly merit another paper. The cost of the tunnel has been exceedingly carefully studied and analyzed, and the percentage of the cost divided under a very large number of heads; but it is impossible to touch upon this matter satisfactorily without going into very detailed explanations, as the cost of the tunnel varied, and must necessarily vary, according to the circumstances under which it is carried out. If a tunnel has to be constructed within a specified time at the highest possible speed, necessitating the working from every possible point and the employment of pumping machinery, the cost must obviously differ immensely from that obtained where working is only carried on from the open end or at such points where pumping presents no great difficulties; while again, the latter cost will vary if the expenditure is limited to a fixed sum per month.

Labor.—Foreign labor was very extensively employed at first, it being utilized, not only in the tunnel in connection with the excavating and timbering of lengths, but also at the winding, pumping and other

engines, and largely also in the fitting shops, brickyard and at other points. Recently it was found possible to dispense with foreign labor almost entirely, with the exception of the English or American tunnel miners necessary for looking after the timbering, and even those were reduced in number, the only other foreign labor employed being the foreman in charge of tunnel masonry, the chief mechanic and two or three assistants, foreman of shops, with two or more good tool hands, foreman of the brickyard and one or two others. The agent, engineers, chief accountant, chief of traffic and some other members of the office staff, are English or American. Local labor, where it could be utilized in place of foreign, was found far more satisfactory, the men being more sober and attentive to their duties, and only requiring constant and careful supervision on the part of the agent and the engineering staff, as already mentioned.

General.—The progress made during the year ending the 15th of September, 1893, is as follows :

Meters of tunnel built	2 036.77
Meters of heading driven	4 420.74

There remained at that date only some 2 667 m. of tunnel to build, and 900 m. of heading to drive.

The greatest amount of tunnel built in any one month during that year was 242 m., and of heading driven, 450 m.; while the greatest advance in tunnel in any one face in a month was 55.50 m. with the treble length system, and in heading, 200 m. The unwatering of the tunnel is now effected entirely by the heading as regards the points in work, and the total discharge per minute is about 3 500 galls.

During the month of July last, heading was being driven in Shafts Nos. 7, 8, 10 and 11, and tunnel built in Shafts Nos. 11 and 12 ; in August, heading in Shafts Nos. 7 and 8, and tunnel in Shafts Nos. 10, 11, 12 and 13.

Latterly it has been necessary to drive the bottom heading again in the center of the tunnel, as the large wooden launder required to carry water through the lengths came into collision with the bricklayers' frame when set for building the invert, the size of the launder or trough being 21 ft. by 4 ft. by 1 ft. 6 ins., and constructed of 2-in. boards. In conclusion the authors of the paper wish to thank the contractor's agent, Mr. J. F. Toomer, for most valuable assistance afforded them.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

726.

(Vol. XXXII.—August, 1894.)

THE SANDROCK SEWERS OF ST. PAUL, MINN.

By GEORGE L. WILSON, M. Am. Soc. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

WITH DISCUSSION.

Situated on both sides of the Mississippi River, the city of St. Paul includes every variety of surface, from nearly vertical palisades extending along the river for miles, to prairies, and from ground below high water in the river (which has a maximum flood stage of 19 ft. above low water) to the higher portions occupied as residence districts, which are from 200 to 300 ft. above the river. The situation of the residence portions on the high ground, on both sides of the river valley, overlooking the business district and the river for miles, is very beautiful; few cities equal, and none surpass, it in natural scenic beauty, as the panoramic views from its bluffs demonstrate.

A portion of the city area 90 to 100 ft. above the river forms a nearly level bench, comprising a district of some 1 100 acres and extending 4½ miles in length, with a width varying from $\frac{1}{5}$ to $\frac{3}{4}$ of a mile. It is of peculiar geological formation and contains a unique system of tunnels for sewers, water works and telephone cables, being, so far as known, the only extensive construction of the kind in America.

This plateau forms a shelf, so to speak, in the gorge of the Mississippi, and is a bench left when the river carved out its deeper and present channel. It is formed by the bottom and hardest portions of the Trenton limestone, of which ledges from 20 to 30 ft. thick remain under this area. This limestone is quarried and extensively used for inside or covered foundation work. Like most limestone, it splits easily, and in a few years disintegrates when exposed to the weather, so that it has been generally abandoned for use in situations exposed to the action of rain and frost. This Trenton formation was originally about 150 ft. in thickness in St. Paul; the portion eroded was of a soft shaly nature with some seams of hard stone, as shown wherever cuttings along the bluffs have exposed the upper strata, which, it may be remarked, abound in fossils.

Over the limestone in the higher parts of the city lie clays and alluvial soils of varying thickness, but in that portion which we consider there are only a few inches or feet above the rock.

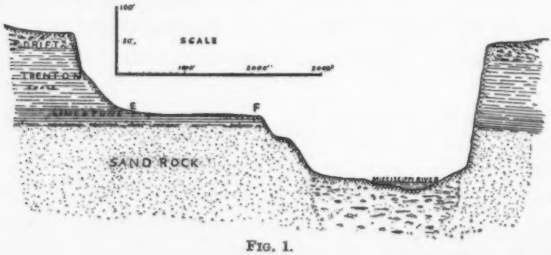
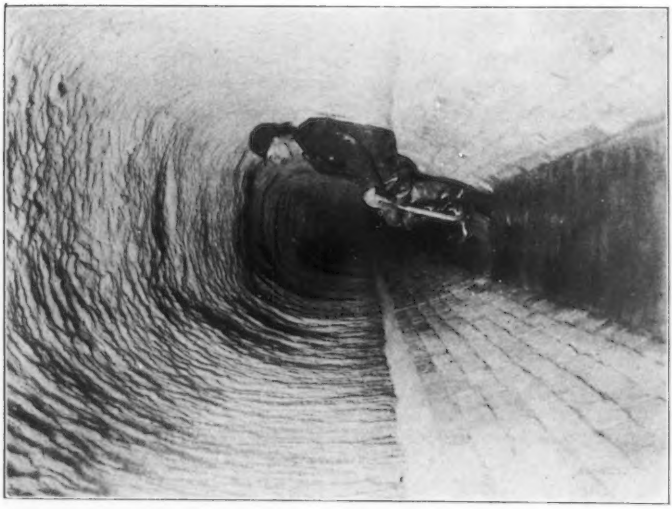


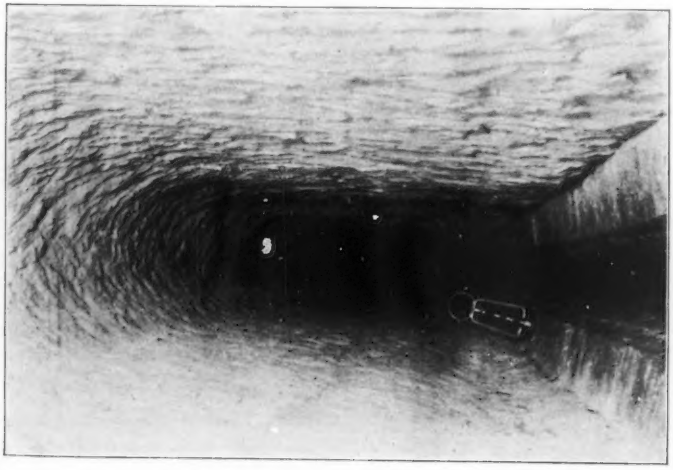
FIG. 1.

Under the Trenton lies the St. Peter sandstone; hardly a stone except in name, as it may be picked and shoveled without blasting. It is nearly a pure quartz sand, the lower strata almost white and the upper of varying shades of yellow. This formation, geologically known as St. Peter sandstone and locally as sandrock, is exposed along the river from 10 miles above to 20 miles below the city. It is about 130 ft. in thickness and lies approximately level from north to south and with a slight pitch to the west of 14 ft. per mile. The elevation of the top of this sandrock is 767 ft. above sea level and 84 ft. above the river, which has an elevation of 683 ft. above sea level.

In this sandstone, easily tunneled, there are many excavations for various purposes. Those of interest to engineers are the subways for

PLATE XXVI.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 726.
WILSON ON SANDROCK SEWERS OF ST. PAUL.





sewers, water mains and telephone conduits. In the first building up of the city the facility for draining the bench land by tunnels in the sandrock led to the construction of many drifts by private individuals, each running from some point at the bluff directly to the land to be drained, without much attention being paid to uniform grade or alignment and without any bottom lining. These have been abandoned as public sewers were constructed. The section of the river valley (Fig. 1) shows at *E F* the portion of the city adapted for this tunnel construction and the geological formation before described.

In 1873 the city (then having a population of 25 000) began to build sewers in this sandrock. In those first built, the laterals were lined with V-shaped inverts. This proved unsatisfactory, and all now have a

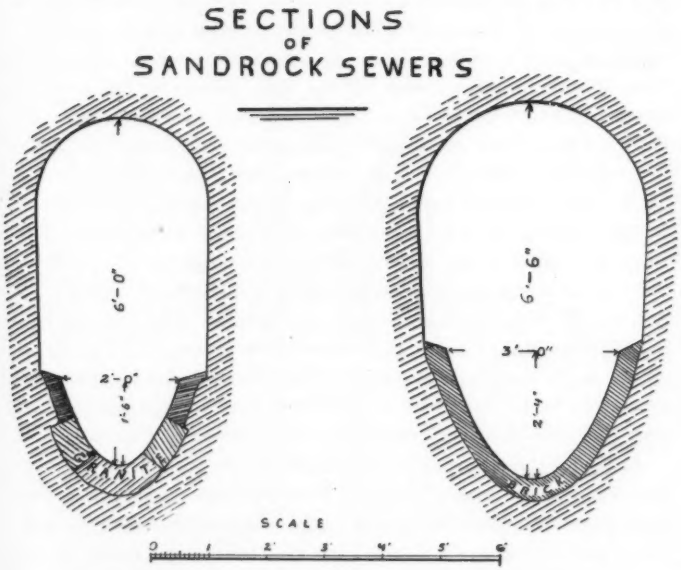


FIG. 2.

channel at the bottom lined with brickwork, usually of a parabolic section. The different sections used vary from 9 x 14 ins. to 4 x 4 ft., while the tunnels range from 2 ft. 6 ins. x 6 ft. to 7 ft. x 7 ft., all having a clear height of at least 6 ft. (Fig. 2). A main sewer running the entire length of the sandrock district acts as intercepter for the dry

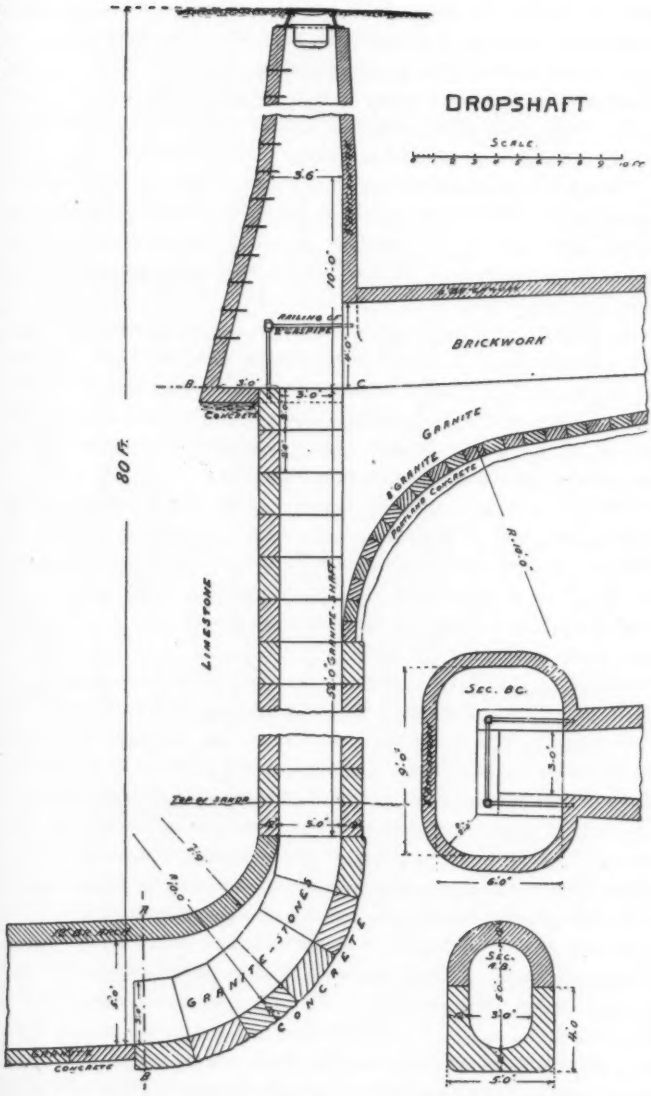
weather flow, while the storm water passes off through proper overflows. The invert, or channel of brickwork in the bottom, is of capacity to carry the ordinary flow and light showers. Storm water from heavy showers rises above the brickwork, but the rock is just hard enough, so that usually there is no appreciable scour. In many of the sewers the pick-marks of original construction are still plainly seen along the sides after 10 and 15 years of use. In places, however, the sandrock is soft enough to require a complete lining; in fact, it is probable that some time in the future these tunnels will be completely lined with brickwork and enlarged to serve as subways for other purposes in addition to their use for sewers, as has been done in Paris.

The grades used range from 0.1 ft. to 10 ft. per 100 ft., the rate of 1 ft. being preferred for the laterals. The rate of 10 ft. per 100 ft. is a necessity for getting down to the river in some of the overflows. On the steepest grades granite lining is used. In passing from open-cut surface sewers on the high ground to the sandrock sewers, difficulty is found in making satisfactory connections; generally a vertical drop in a granite-lined shaft is used (see page 199), or by a "slope" from the upper to the lower sewer if the depth is not too great. The bottom of the shaft is preferably a well at bottom instead of the section shown. The limit of economical construction is where the grade brings the roof of the sewer against the overlying rock, or the depth of limestone and earth above is such that it is too expensive to reach the tunnels from the surface. The views on Plate XXVI show actual construction in two of the sewers.

The depth from open-cut sewers to the tunnels, which usually end at the foot of the bluffs, is from 20 to 75 ft. Through the sandrock district the depth to sewer from the surface is between 25 and 60 ft.

In the construction of the tunnels, shafts are sunk at street intersections, from 300 to 600 ft. apart. These are built up with brickwork from the solid rock to the street surface and provided with manhole covers, and at convenient points with iron ladders for access to the sewers.

The lines are transferred from the surface by plumb-bobs in the shafts and fixed below by wooden plugs placed in the roof of the tunnel. Grades are given on similar plugs placed on the sides. The drifts are opened through between shafts, then trimmed to form, and the bottom carefully shaped to fit the brickwork, which is then laid accu-


DROPSHAFT
SCALE
BRICKWORK
GRANITE
LIMESTONE
80 Ft.
SEC. BC.
SEC. AB.
GRANITE
CONCRETE

rately to grade and line. Owing to the short length of headings, usually no artificial ventilation is required, more particularly as most of this work is done in the winter, as labor is cheaper at that time and this is work that can be done then better than at other seasons. When ventilation is required, a small rotary fan is placed at the surface with 3-in. air pipe leading down to the heading.

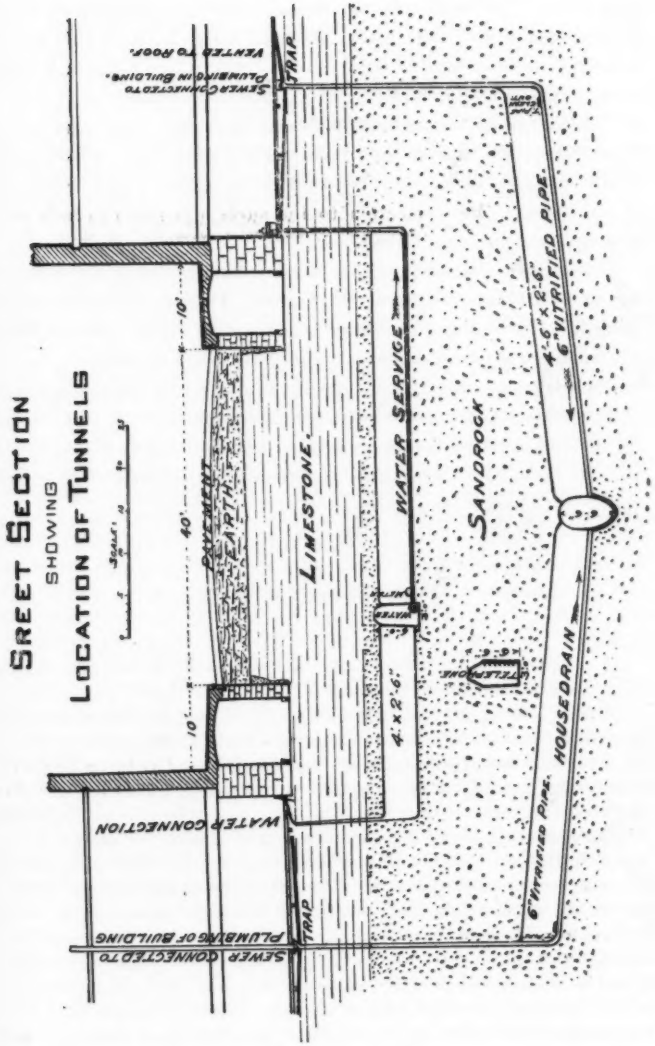
The tools used on this work are simple, the picks only are of special construction. The waste (muck) is loaded into buckets, wheeled to shafts, and hoisted by windlass operated by hand-power. The amount to be removed at one time being small, this is found to be the most economical method.

As to cost, the price of excavating and removing waste, use of tools and lights, averages $1 10 per lineal foot for smaller sizes; sinking shafts, $3 per foot in depth; brick lining laid in American hydraulic cement, $20 per M. The average cost per foot of all sizes may be put at $3, which will include shafts and catch basins; the cost of these with connection to the sewer is $150 each.

There are 20 miles of these subways in the city at present, and a considerable part of the area mentioned is not yet built up. About $300 000 has been expended in this work to date. House connections are made for a price of 85 cents per lineal foot of horizontal and vertical distance. This includes the 6-in. pipe which is laid to the main sewer.

The house-drains are connected with the main sewer through a small tunnel at right angles to the street, running back to the property to be drained. A 4-in. or 6-in. drill hole is made through the rock, the plumbing connected at the upper end, and a 6-in. or 9-in. vitrified pipe run from the lower end out to the main sewer. At the bottom of the vertical pipe a T connection with clean-out is placed, and the pipe in the side tunnel is covered with concrete. Connections with catch basins are made in a similar manner, except in the drift where a brick invert is laid instead of a vitrified pipe (see page 201).

Besides the sewer tunnels, there are some four miles of water pipes, in separate tunnels, located on the side of the streets and above the former. In size these are 3 x 6 ft. Pipes in these tunnels are of 4-in., 6-in. and 12-in. sizes. These pipes are in no possible danger from frost or surface disturbances, and the whole system is open to inspection or repairs at any time without opening the street. The method of


STREET SECTION
SHOWING
LOCATION OF TUNNELS
SCALE
PAVEMENT
EARTH
LIMESTONE
WATER SERVICE
SANDROCK
4'-6" x 2'-6"
6" VITRIFIED PIPE
HOUSE DRAIN
4' x 2'-6"
6" VITRIFIED PIPE
WATER CONNECTION
TRAP
SEWER CONNECTED TO PLUMBING OF BUILDING
VENTED TO ROOF
SEWER CONNECTED TO PLUMBING IN BUILDING
40'
10'
10'

putting in service pipes from the buildings is very simple. A drift is run out at right angles to the street under the building to be connected, and a drill hole made from the cellar to the drift, and the service pipe run from the cellar to the main, where a meter is placed secure from meddling and easy of access.

The construction of telephone subways has been commenced. These are of the same general form and size as the water-pipe tunnels, and have space at the sides for eight or ten cables. For distribution to subscribers, one connection to the surface is made in each block and surface wires run in the block.

The city of Minneapolis has used a similar construction for its sewer outlet tunnels below St. Anthony Falls to a limited extent. Here it has been found necessary to completely line all the tunnels as the sandrock is more friable and holds more water in seams.

This is an account of how one city has been able to solve a portion of the subway question for a limited part of its area. There are, perhaps, no other cities having geological features that would make this plan feasible, for, like other engineering expedients, it has been worked out to suit the environment.

DISCUSSION.

A. F. NOYES, M. Am. Soc. C. E.—I would like to ask Mr. Wilson what method he used for ventilating the sewers?

J. T. FANNING, M. Am. Soc. C. E.—Mr. Wilson has mentioned that Minneapolis uses a similar system of sandrock sewers. The discharge of the main outfall sewers at Minneapolis is into the river below the Falls of St. Anthony. These outfalls are at a level about 100 ft. below the street surfaces drained by them, and the surface system of sewers discharges into the low level outfall in a vertical shaft. There is a strong upward draught through this vertical shaft which thoroughly ventilates the tunnel sewer below. The tail-races of the mills at Minneapolis are tunneled in the sandrock in a similar manner, and in this respect are similar to the Niagara power tunnel. Mr. Wilson said the surface rock in St. Paul is the Trenton limestone. The similar limestone in Minneapolis is about 12 ft. thick in the river-bed at the crest of the falls and rests upon the sandrock. The tail-races of the mills are tunneled immediately beneath the firm lime rock, and this rock forms the roof of each tunnel. The dam and forebay leading water

to the turbines rest upon the lime rock, and beneath the forebay a vertical shaft is cut to the tunnel below and the turbines are placed in these vertical shafts so as to discharge their water into the tunnel tail-races below. This system of tunneled tail-races is still followed at the mills in Minneapolis.

DESMOND FITZGERALD, M. Am. Soc. C. E.—Are the tail-races lined?

Mr. FANNING.—The original tail-races were lined with wood. The flow of water from the turbines does not usually fill the tunnel to the roof and the lining was not usually carried up so high as the limestone roof, but only a little above the ordinary level of water in the tail-races. Some of the older tail-races and the more recent tunneled tail-races are lined with masonry. The sandrock, usually called St. Peter sandstone, resists the effects of the atmosphere very well except near the mouths of the tunnels where frost action disintegrates it; but it is necessary to line these tunnels, to protect the rock from erosion by a current of water.

K. E. HILGARD, M. Am. Soc. C. E.—I do not know that I can add anything pertaining to the sewers, but I wish to state that I have always been impressed by the geological conditions existing at St. Paul, Minn. Over a great part of the city, they are very favorable to certain building operations. Removing a little top soil, the limestone is found in almost level ledges, easily removed and easily worked, furnishing sufficient and well-adapted material for cellar and basement walls to stand on the best of firm foundations.

Besides, everyone in St. Paul is proud of the beautiful white sandrock bluffs. Nature itself teaches us instructive methods. I have often admired the work of hundreds, nay, thousands, of birds in the soft sandrock, into which these winged creatures dig their little caves. Men, likewise, have taken advantage of this condition, and have at times dug out of this rock places to live in, and even in early times Indians have used caves as dwelling places that exist to this day.

D. J. WHITTEMORE, Past President Am. Soc. C. E.—It would be very gratifying to the citizens of St. Paul could they feel sure that the sewers they have constructed in sandrock would not in time require lining.

In 1856–57 the Chicago, Milwaukee and St. Paul Railway Company constructed a tunnel through similar rock, at the dividing ridge between the Wisconsin and Mississippi rivers. Immediately after its construction it required timber support, and when this timber became decayed, it was found cheaper, and certainly safer, to build a new tunnel and line it with brick than to attempt to utilize the old one. The rock at St. Paul is so soft that one can bore into it with an auger, and birds excavate holes in it for their nests. Jonathan Carver over 100 years ago describes the rock as being the home of the birds. Perhaps some of the members will call to mind a very inter-

esting paper read at the Minneapolis convention by the late Colonel Farquhar upon the preservation of the Falls of St. Anthony, which falls, through erosion of this soft rock, was being disastrously affected.

Nearly 40 years ago I was camped with a party near an Indian cave in this rock mentioned by Carver, and there was then evidence inside it of continuous erosion..

I desire further to add that the line of the Chicago, Milwaukee and St. Paul Railway passes for a long distance along this sandrock bluff in St. Paul, and also at Fort Snelling, and that within the last three or four years great expense has been had in building retaining walls to protect against erosion of this rock, as each successive season through climatic effects would cause 1 ft. or more to shell off the steep bluffs and undermine the overlying limestone ledge, thereby endangering traffic. I state this as only tending to indicate that in time it may be found necessary to give the sewers in this rock at St. Paul an adequate lining.

GEORGE L. WILSON, M. Am. Soc. C. E.—In reply to Mr. Noyes' question, I would say that the sandrock sewers are ventilated by the shafts at street intersections. These serve as manholes and are all provided with ventilated covers.

In the drop-shafts the current of air whenever the water is falling is always down, thus drawing the air from the sewers above and forcing it in a stream into the sewers below.

The trouble spoken of by Mr. Whittemore is along the exposed bluffs, and is due to the action of sun, wind, and especially frost, neither of which affect the sewers. It is probable that at some time in the future the sewers may be lined, and the sections used are of such form that the upper part can be lined without changing the invert first put in. The rock at Minneapolis spoken of by Mr. Fanning is softer and charged with water, which makes the lining of the tunnels there a necessity.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

727.

(Vol. XXXII.—August, 1894.)

A FEW REMARKS ABOUT THE NIAGARA GORGE.

By L. L. BUCK, M. Am. Soc. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

WITH DISCUSSION.

Various scientific societies have discussed this gorge and in some cases attempts have been made to estimate the length of time required by the river to excavate the chasm as it now exists. But there are some of its features which appear to have been overlooked in such papers as have come under the writer's observation, and which he has thought might be of interest to our members while they are here, where they will be able to examine and study the question for themselves. It presents abundant opportunities for the development of theories. The writer has had various theories about it, but should any of them become evident in this paper he warns anybody who attacks them that he may suddenly find him on his side regarding them.

To simplify the following description, the gorge has been divided into six parts, as follows:

A B, 11 500 ft. long; *B C*, about 4 000 ft.; *C R*, about 1 200 ft.; *R D*, 2 000 ft.; *E F*, 3 200 ft.; *F H*, 3 700 ft. These distances are

but roughly approximate, and obtained by scaling. The portion *A B*, beginning at the falls, is generally about 800 to 1 200 ft. wide at the water surface, has but slight descent and a rather slow current, and along its axis, as shown by the soundings, depths of 120 to 190 ft., the latter depth being toward the upper portion. This is the only portion in which soundings have been taken.

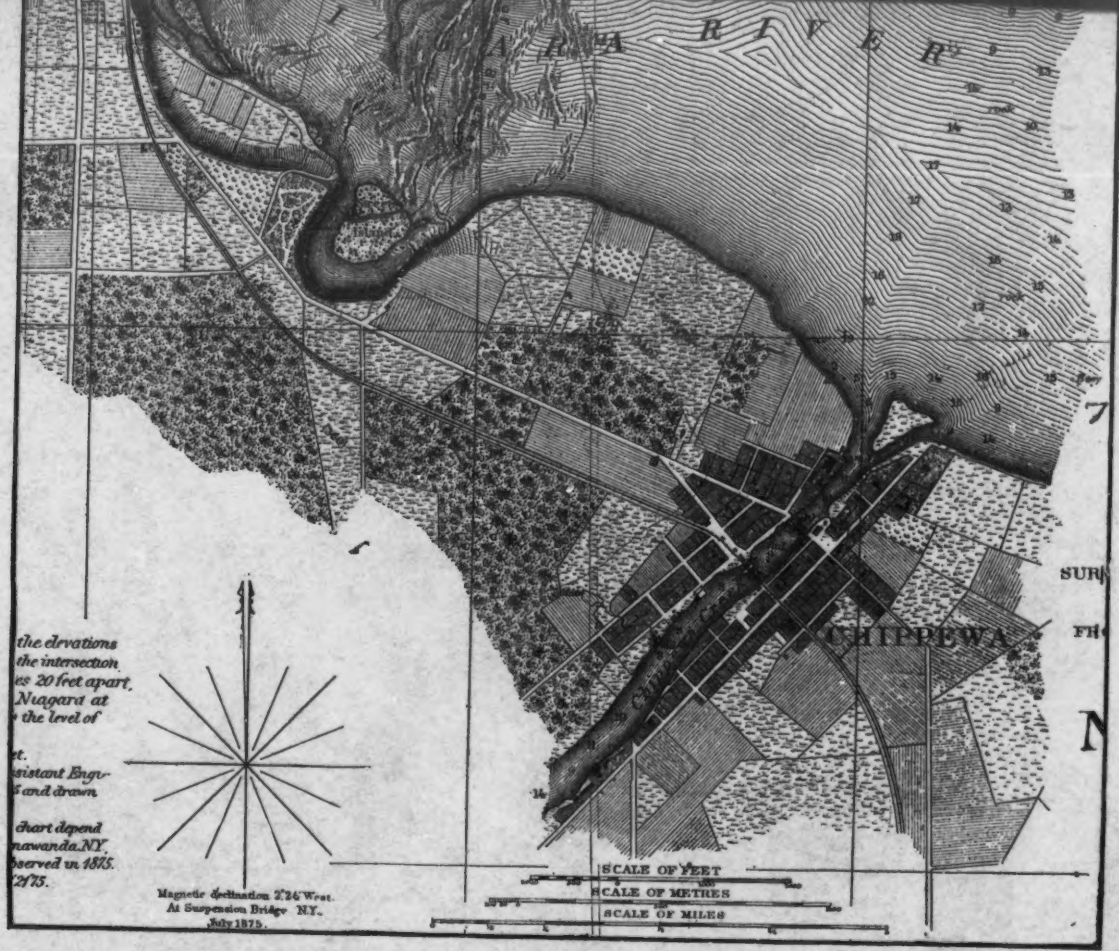
B C, at the water surface, has a width of about 400 ft., a descent of about 26 ft., and, as would be expected, a tremendous current, very much broken up and about 10 or 12 ft. higher in the middle than at the edges.

C R, at the water surface, has a width of about 600 ft., a descent of about 2 ft., current decreasing and becoming smoother at *R*.

R D, the portion known as the Whirlpool, has at the surface a length of 2 000 ft.; width, 1 100 ft. The outlet *E*, on the right-hand side, is about midway between *R* and *D*. The axis of the current from *R* approaches the right side, and while some of the water flows directly through the outlet, the greater part flows past the outlet, impinges against the shore at the right of *D*, turns to the left and circles around till nearly opposite the outlet, where, meeting the portion coming down the left side, both currents are driven toward the outlet, and, passing under the former current, come boiling up at the outlet and flows through it in a new direction at an angle of over 90° from its former direction. Beyond *D* is a ravine, down which a small brook flows and empties into the Whirlpool at *D*. *E F* has a surface width of 600 ft., a descent of 4 or 5 ft., and a considerable current.

At *F* the surface suddenly narrows to about 300 ft. in width, with an increasing current and a descent of 7 or 8 ft., to *H*, where the width becomes about 900 ft.

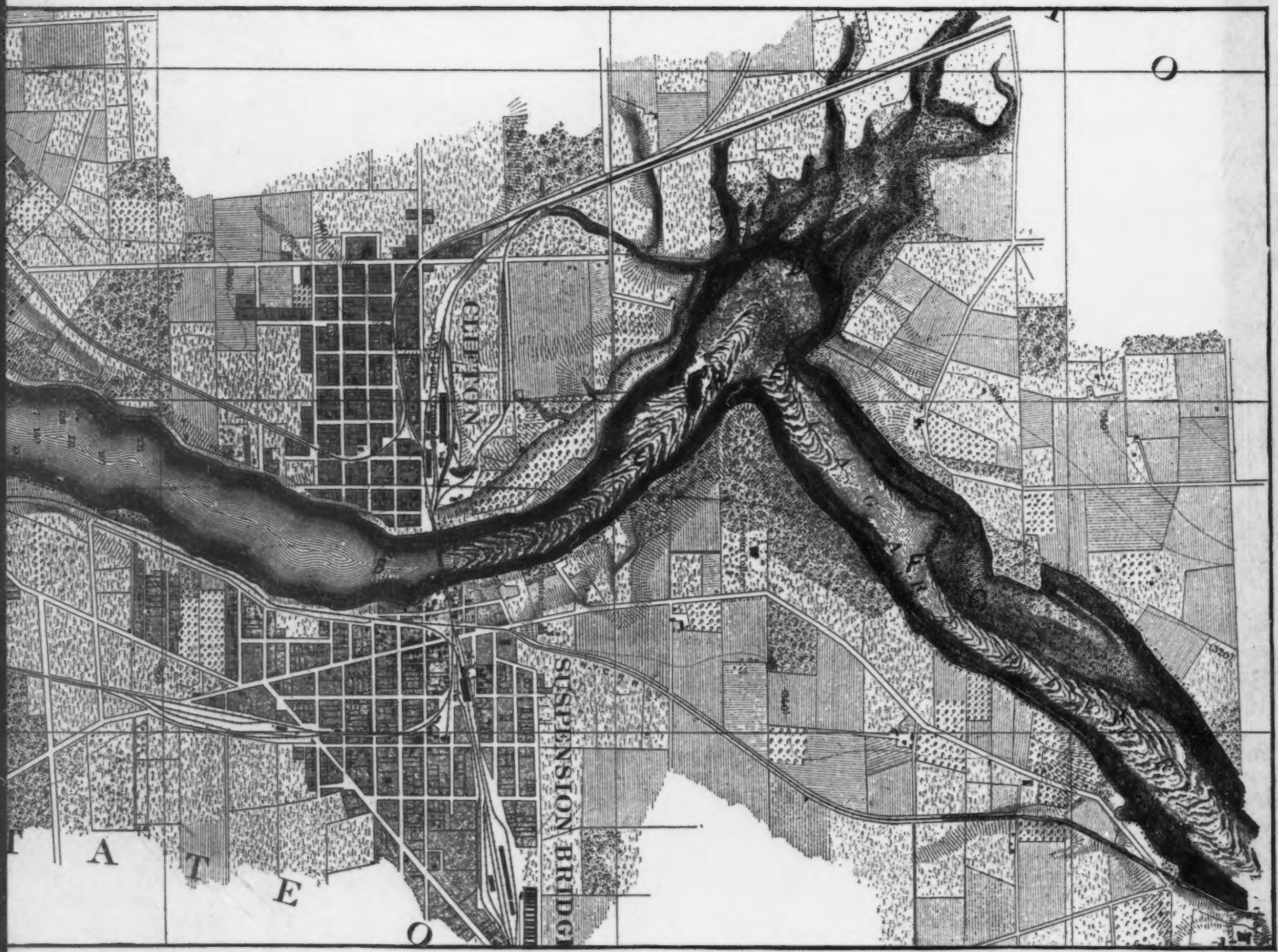
Throughout the whole distance the sides of the gorge are vertical at the top, and next to the Horseshoe the vertical portion extends nearly to the lower surface. Below this point the banks are vertical or overhanging, with heights of 30 to 60 ft. Below this, a slope formed of the débris from the sides, with inclinations of 35 to 45°, extends to the water's edge. The upper stratum of rock is generally 10 to 15 ft. thick, of limestone, possessing considerable strength, but flakes off slowly by exposure to the atmosphere. This is succeeded by limestone shale, blue shale, more finely stratified limestone and red sandstone, red shale and limestone strata with clay seams.


NIAGARA RIVER
CHIPPEWA
the elevations
the intersection
es 20 feet apart,
Niagara at
the level of
t.
sistant Engr-
and drawn
chart depend
nawanda NY,
bserved in 1875.
2/75.
Magnetic declination 2°24' West.
At Suspension Bridge N.Y.
July 1875.
SCALE OF FEET
SCALE OF METRES
SCALE OF MILES

NIAGARA FALLS
NIAGARA RIVER

SUSPENSION BRIDGE
CLIFTON

PLATE XXVII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 727.
BUCK ON NIAGARA GORGE.



The existence of the great falls is due to this arrangement of the formation. The water falling over the edge of the top stratum excavates the softer materials below, until the top stratum projects so far out that its own weight and the superincumbent water causes it to break off.

From the soundings below the falls, as well as from a study of the Genesee Falls at Rochester, where the formation is very similar, it appears that generally the fall excavates to a depth below the lower surface about equal to the height of the fall above that surface.

Judging from the generally uniform conditions existing from *A* to *B*, it is reasonable to suppose that the excavation throughout the 11 500 ft. has gone on at about the present rate. If so, it would have occupied a period of about 4 000 years. This applies only to a little over 2 miles of the 7 miles of gorge, or less than one-third of the distance.

At *B* the conditions are abruptly changed. The chasm becomes but about half as wide as at *A B*. Although no soundings can be taken, there is good reason to suppose that the depth does not exceed 80 ft. Then there is the rapid descent of the surface. One feature exists in the formation in this portion which does not occur in the former portion, in the fact that here we have a second strong stratum of rock about 12 to 14 ft. thick, located about 115 ft. below the top one, and suggesting that it may have caused the fall to be divided into two parts, the lower following the upper. This argument is also supported by the fact that immediately overlying this second strong stratum is a stratum of blue shale 50 ft. thick, which would be rapidly disintegrated by a heavy volume of water falling upon it, or if, with a fall of 115 ft., it suddenly brought up against the second smooth stratum, which would deflect a considerable portion of it laterally and violently against the shale. The excavation here would be much more rapid, and consequently make the gorge narrower.

The Whirlpool appears to indicate that there must have been a great cavity in the rock, although some writers have advanced the theory that at one time the river continued in the direction of *R D* produced, and after excavating the gorge up to about the present outlet became dammed by glacial action or some natural convulsion, which diverted the water into its present course. This may be the most reasonable theory.

The third striking feature is that at *F H*, where the great protuberance *G* juts out from the left bank, with a considerable ravine between it and the bank, and extending from the lower end about half way to the upper end.

There may have been a long, narrow island about over the highest part of this protuberance before the falls reached this part. This would divide the stream, the larger channel to the right. Such larger channel would cut more rapidly and deeper than the other one, so that by the time the smaller had cut about half way up, the larger would have reached the upper end of the island, and would then divert the water from the smaller channel to itself. The island afterwards would crumble down to its present form.

It must be constantly borne in mind that at whatever point the falls have been, the river above them has spread over a much greater width than that of the present gorge, and that the falls themselves always left the gorge narrower than we now find it, to be afterward widened by atmospheric influences.

In the remaining two miles the gorge presents some features of minor interest, but none so striking as those described.

DISCUSSION.

F. Lynwood Garrison, Assoc. M. Am. Soc. C. E.—As the length of time in which the Niagara gorge could have been eroded by the action of the falls is a subject upon which there is some difference of opinion among competent geologists, it would seem that Mr. Buck's estimate of 4 000 years as the probable period necessary to effect this excavation from the whirlpool rapids to the present site of the falls is somewhat arbitrary.

Our knowledge of geological phenomena has of late years undergone such modifications that I think it is doubtful if geologists are agreed that the formation of this gorge has been necessarily due entirely to the erosion; there seems to be some disposition to attribute at least its primary existence to a fault, crack or dislocation of the Niagara limestone and its underlying shales.

The State Geologist of New York, Professor Hall, and the famous English geologist, Lyell, both estimated the average rate of erosion by the falls at 1 ft. per year. Professor Dana considers their estimate large. Desor calculated the erosion at about 3 ft. per century. Estimating

the total length of the gorge from Queenstown to be 6 miles, at the rate of 1 ft. per year 31 000 years, and at 1 in. per year, or about 8⅓ ft. per century, 380 000 years would elapse before the falls would reach their present location. Blakewell, I believe, estimates the rate of recession at 3 ft. per year. Professor Archibald Geikie considers Lyell's estimate as the more probable conjecture.

If Mr. Buck's calculation of 11 500 ft., as the distance between the falls and the whirlpool rapids is correct, and if we accept Blakewell's estimate of 3 ft. per year, Mr. Buck's calculation of 4 000 years would appear to be about right. Admitting the gorge was formed by the action of the water, which has been by no means proved, and was not due to any other cause or causes, it seems to me this estimate of 4 000 years is altogether too small. The consensus of opinion of geologists would seem to be nearer that of Lyell's estimate of 1 ft. per year, than any other; at this rate the gorge along the line *A B* would require about 12 000 years. Professor Geikie, I believe, maintains that the entire gorge was formed by the erosive action of the falls and was not due to any dislocation, rent or fault in the rocks.

Robert Fletcher, Assoc. Am. Soc. C. E.—It may be well to call to mind some geological opinions on this subject. It is well known that Lyell's estimate of the time required to excavate the Niagara gorge exceeded 100 000 years. I have the opinion of a geologist who has made considerable study of the subject, to the effect that opinions among geologists have been much modified in recent years, and that the disposition is now to place the time very much less than that, certainly not more than 10 000 years, and with the tendency to reduce even that figure.

Joseph P. Frizell, M. Am. Soc. C. E.—I want to say a word on the gorge as the result of abrasion. It seems to me that there is a very trustworthy criterion to determine whether this gorge resulted from a natural process of abrasion such as is now going on, or was determined by a fault in the rock. The river above the falls is some 5 000 ft. wide, while the gorge is scarcely more than 1 000 ft. Now, if we assume that the river once flowed from Lake Erie to Lake Ontario, as it now flows from Lake Erie to the Falls, and that, by the natural process of abrasion, by the undercutting of the cataract and the fall of the superincumbent rock, the falls have receded to their present position, this history would be plainly written in the adjacent topography. We should find along this gorge, and on both sides of it, the banks, the deposits and the abrasions incident to the flow of a wide and swift stream. Whereas if the present course of the river had been originally determined by a fault in the rock, these indications would be wanting. I do not know whether such topographical features exist, but it seems to me that this is the true criterion for verifying or disproving the hypothesis of a fault.

HOWARD J. COLE, Assoc. M. Am. Soc. C. E.—It seems to me that if this gorge had been formed by the abrasion of the rock there would be some indications of it in the lake. The river ought to deposit the material accumulated from the decomposition of the rocks in a peculiar form of natural shelf soon after it enters Lake Ontario. I would like to ask Mr. Buck if he has any information about this, and whether soundings have been taken in the lake that show indications of a deposit.

L. L. BUCK, M. Am. Soc. C. E.—I cannot inform anybody regarding the deposit in Lake Ontario, as I have never made any investigation there.

Mr. COLE.—It would not begin to deposit the material until it enters the still water of the lake.

Mr. BUCK.—Yes; it might deposit some in the river below the mountain. Supposing the falls commenced at the mountain they would be apt to excavate a considerable basin below, both as to width and depth. The material of such excavation would be carried to the lake; then when the falls had receded to some distance, this basin would retain some of the disintegrated material.

Mr. COLE.—I have seen a somewhat similar case of a brook coming down a mountain side, carrying in suspension gravel and earthy matter scoured from its course, finally emptying into a small pond where it formed a shelf of this material and extended this shelf out until it very nearly filled the mill pond. I think the Niagara River would act on the same principal if the gorge was formed by abrasion.

Mr. BUCK.—Not wishing to take too much time here that may be required on some more profitable paper, I would say that this paper was written to call the attention of the members, while on the spot, to the peculiarities of the gorge and to point out the portions where, at various times in the past, the conditions must have been different from what they are at present.

Answering the question as well as I can:

There is the heavy stratum at the top of the fall, over which the water breaks, but further inland there are some finer strata overlying the heavy one. Above the falls, in the channel, these finer strata crumble away and form the rapids as they exist above the falls. The material below the heavy stratum is of a more frail nature. As before stated, there are thin strata—some very thin. There are some very thick strata of blue shale which do not withstand the action of water and air. These fine strata and the shale are torn out by the water, assisted by the air which gets behind the falling sheet of water, until the process has excavated so far back that the weight of the projecting shelf, with the superincumbent water, becomes too great for its strength, when large masses of it are broken off and fall into the channel below. They doubtless get still further broken up in falling,

and again by succeeding pieces falling upon them. Most of these large pieces probably remain in the bottom. It is not likely that any of these large masses, or even any masses, are carried to the lake. Hence I concluded that the material, like the shale and clay, must be in sufficient proportion to the whole that, together with the very finely disintegrated stone, their removal will leave the channel in its present form; and such portions are mostly carried well out into the lake before they are precipitated.

J. T. Fanning, M. Am. Soc. C. E.—The upper Mississippi River presents an interesting example of the erosion of a river-bed at a fall. There is a gorge excavated by the Mississippi River extending from Lake Pepin about 50 miles up stream to St. Anthony Falls, in Minneapolis. When the lumbermen began building their mills, in 1855, the falls were found to be receding rapidly. The bed of the river at the falls is a firm limestone about 12 ft. in thickness, and beneath this limestone is the soft St. Peter sandstone. The fall was about 50 ft. in height, and eroded the stone below and undercut its limestone cap, leaving the limestone as a projecting shelf. The weight of the water at the fall broke off this projecting shelf, usually in widths of about 12 ft., when the process of undercutting and breaking off would be repeated. It was found in 1856 that the falls were receding by this process of undercutting and breaking, about 100 ft. per year. This limestone cap becomes thinner as it extends up stream, and about 1 500 ft. from the crest of the falls it disappears entirely, and the bed of the river from this point upwards a considerable distance is the soft sandrock. There was danger that the limestone would be soon cut entirely away, when the falls would recede at a much more rapid rate. The millers and citizens of Minneapolis made a desperate attempt to stop this undercutting and recession of the falls, and the Government finally came to their assistance and covered the falls with a sloping timber apron. This timber apron was described in a paper read before this Society by Colonel Farquhar, a member, in June, 1883.

Charles H. Snow, Assoc. M. Am. Soc. C. E. (by letter).—It should not be understood, as it may be from something said in discussion, that all hard rock resists the action of water better than all soft rock. Water acts upon rock in two ways—mechanically and chemically. In the former, hard rock may resist abrasion better than soft. In the latter, action results from some chemical in the water, as carbonic acid, or else from some substance in the rock which will oxidize on contact with water, as iron sulphide. Chemical action is, then, independent of hardness, so that soft rock may resist its influence even better than hard. The action of water on hard rock is sometimes surprisingly rapid. Lyell mentions the case of the Simeto, in Sicily, which had been dammed by lava in 1600 and which by 1850 had a new channel, in parts 200 ft. deep and 40 to 50 broad. In the same connec-

tion, I recall in Oregon a mass of hard volcanic matter 500 or 600 ft. high, a face of which had been eroded down to much below the original surface. A drift for mining purposes into the hill immediately below the trap encountered trees of considerable size, portions of which were hardly, if at all, altered from the condition in which they were when enveloped by the lava flow, so that they had to be removed by the axe. Yet other portions of the same trunks were perfectly silicified and could be removed by the sledge alone. The same tree would afford a series all the way from woody fiber to wood opal. How long it took for the 500 or 600 ft. of lava to be cut through I had no means of determining, but it was not long enough for the trees to have become entirely silicified.

A result noticed for the first time at Niagara Falls is the abrasion due to the movement of the air currents caused by cataracts. It is the spray sent off at the impact of the water and further propelled by the winds that excavated the cave under the falls.

It would be interesting to know whether the gorge further widens by the side action of the current as it flows past—an influence to which the vertical sides of cañons are usually due. Also, whether the rapids above the falls are caused by unevennesses in the rock texture, harder rock presenting a check to even wear, and thereby causing ripples or waves.

The question has arisen as to whether a bar exists at the mouth of the river. As material deposited in a swift current is sorted by the current, the only matter which would remain influenced by the current where the quiet of the lake is encountered would be small particles or pebbles, the large pieces dropping when the current begins first to be checked.

Mr. Schneider's paper on the cantilever bridge tells us that the bridge is founded on such large rocks from the hard upper strata.

Mr. Buck (by letter).—In reply to Mr. Frizell's discussion regarding the evidences of water having flowed over the surface of the rock at the sides of the gorge, it will be noticed that at various distances back from the brink of the gorge the original banks of the river still exist generally well defined. At Suspension Bridge and on the opposite side of the river the upper surface of the top stratum of rock shows abundant evidence of the water having flowed over it.

In reply to Mr. Snow's remarks about the side action of the current in the gorge below the falls, there is no appearance of erosion from this cause. The gorge does widen after the falls have passed onward. The cutting, or rather the breaking and tearing away, caused by the falling water, leaves the gorge much narrower than it afterwards becomes, and with nearly vertical or even overhanging sides. The rock, being of a nature which does not bear exposure to the atmosphere, continues to fall off, and gradually forms the slopes of débris seen on

each side. This action is especially notable each season of the year when the frost is thawing out of the banks.

It is very possible that a fissure may have existed in the vicinity of the whirlpool, and for a long time I was disposed to that view of it, from the fact that the form of the gorge at that point would suggest a three-way fissure, and that the conditions indicated a very much more rapid action from the whirlpool to a point above the railroad suspension bridge than now exists. A closer examination of the formation existing under the bridge satisfied me that, at least, the fissure theory was not necessary to prove rapid cutting, as it is much less fitted to withstand the action of the falling water than the portion nearer the present falls. Moreover, a fissure of large dimensions is generally due to an upheaval, causing the strata to dip each way from the fissure. So far as I have been able to discover, they do not so dip. At Suspension Bridge there is a slight dip, but it is in the same direction on both sides of the river, viz., easterly, and the dip appears to have been continuous across where the gorge now exists.

Finally, when any geologist advances the theory that Niagara Falls have been employed 100 000 years in cutting the present gorge, it is safe to say that either he has never examined the formation closely, or that he has no conception of the prodigious effect of such a vast body of water falling 160 ft. One passage through the Cave of the Winds, where it needs a strong man to withstand the air-pressure caused by a comparatively thin stream of water, will give one some idea of what it must be behind the Horseshoe Fall, where the sheet of water is about 30 ft. thick, if not even more than that. The motion of the air alone would be very destructive, and when laden with water is still greater.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

728.

(Vol. XXXII.—August, 1894.)

THE PULP MILL OF THE CLIFF PAPER COMPANY OF NIAGARA FALLS, N. Y.

By WALLACE C. JOHNSON, M. Am. Soc. C. E.

READ AT THE ANNUAL CONVENTION, JUNE, 1894.

WITH DISCUSSION.

Previous to the completion of the tunnel and canal of the Niagara Power Company, the only water power available at Niagara Falls was that furnished by the Niagara Falls Hydraulic Power and Manufacturing Company.

The water used by this company is drawn from the river at a point above the head of the rapids about a mile above the falls, and conveyed through the city to a point about one-half mile below the falls by a canal 4 400 ft. long. The canal discharges into a basin running nearly parallel with the edge of the high bank and about 350 ft. from it. From this basin water is drawn to supply about 10 000 H. P. to the various mills shown in Fig. 1.

The universal method of using this water, previous to the construction of the plant under consideration, had been to sink a shaft at some point between the basin and the edge of the high bank to a depth of

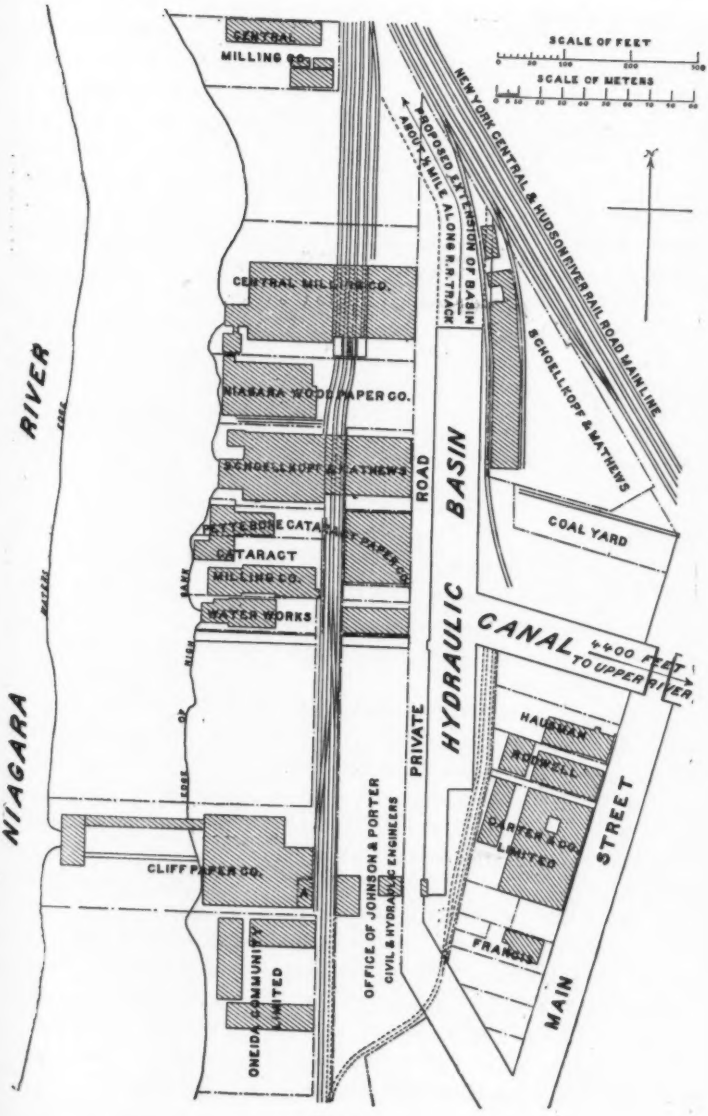

SCALE OF FEET
SCALE OF METERS
NEW YORK CENTRAL & HUDSON RIVER RAIL ROAD MAIN LINE
PROPOSED EXTENSION OF BASIN ABOUT ¼ MILE ALONG R.R. TRACK
CENTRAL MILLING CO.
NIAGARA WOOD PAPER CO.
SCHOELLKOPF & MATHEWS
SCHOELLKOPF & MATHEWS
COAL YARD
CATARACT MILLING CO.
WATER WORKS
CANAL
4400 FEET TO UPPER RIVER
HYDRAULIC BASIN
PRIVATE ROAD
NIAGARA RIVER
HAUSMAN
ROEBLING
CARPER & CO. LIMITED
FRANCIS
MAIN STREET
CLIFF PAPER CO.
ONEIDA COMMUNITY LIMITED
OFFICE OF JOHNSON & PORTER CIVIL & HYDRAULIC ENGINEERS

FIG. 1.

from 50 to 100 ft., to place in the bottom of this shaft vertical turbine wheels, and discharge the water from the bottom of the pits upon the face of the bank, as shown in Plate XXVIII, which is from a photograph of the bank, showing the mills and the water discharged from the various pits.

The reason for this wasteful use of the water lay in the fact that at the time these various mill sites were sold, the power company did not own the sloping bank. The original deeds to the builders of the canal only conveyed the title to the land to the edge of the high bank and granted the right to excavate to a depth of 100 ft. and discharge the tail-water over the sloping bank to the river.

To all of the mills fronting on the hydraulic basin north of the water works, shown on Fig. 1, the right to draw water from the basin had been sold or leased.

In 1881 the Niagara Falls Hydraulic Power and Manufacturing Company sunk a shaft for a wheel pit at the point *A* (Fig. 1), 20 x 40 ft., and about 80 ft. deep, and drove a tunnel from the bottom of the shaft to the face of the bank for the discharge of the tail-water.

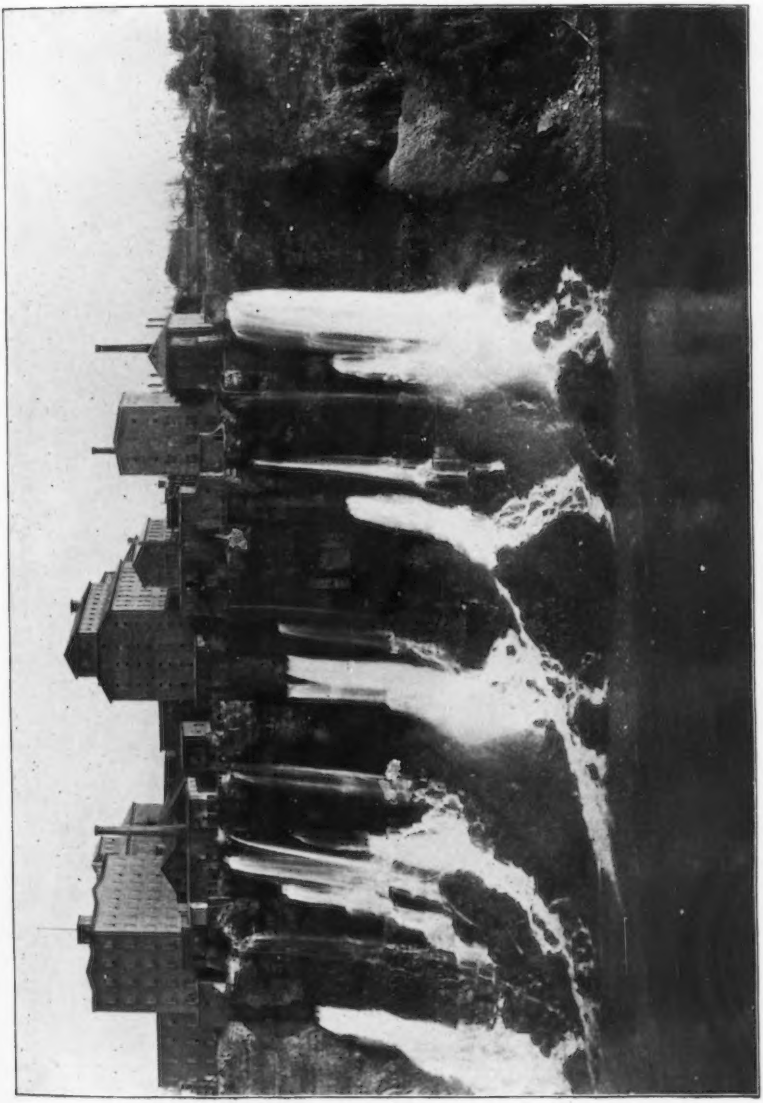
Three turbine wheels have been placed in the bottom of this shaft capable of developing about 1 700 H. P. From these wheels power is delivered into the factories of the Cliff Paper Mill above the bank, the Oneida Community, Limited, and all the mills fronting on Main Street, as shown in Fig. 1. This pit, wheels and turbines are shown in section on Fig. 2.

Until within the past year all the water discharged by these wheels was poured out from the mouth of the tunnel at an elevation of about 125 ft. above the water in the lower river.

The writer entered the service of the Niagara Falls Hydraulic Power and Manufacturing Company, as engineer, in 1886, and soon after that time the company acquired the lands on the sloping bank between the face of the cliff and the water of the lower river, giving it the right to utilize the full available head of about 215 ft.

The company owns a strip of land 100 ft. wide from Port Bay, the point where the water is taken into the canal through the city to their lands where the mills are located. The canal, as originally excavated in this strip, was only about 35 ft. wide and 8 ft. deep. The capacity of this canal was about 13 000 H. P. if used under the full head of 210 ft. As the wheels had been put in, only about 6 000 H.P. were

PLATE XXVIII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



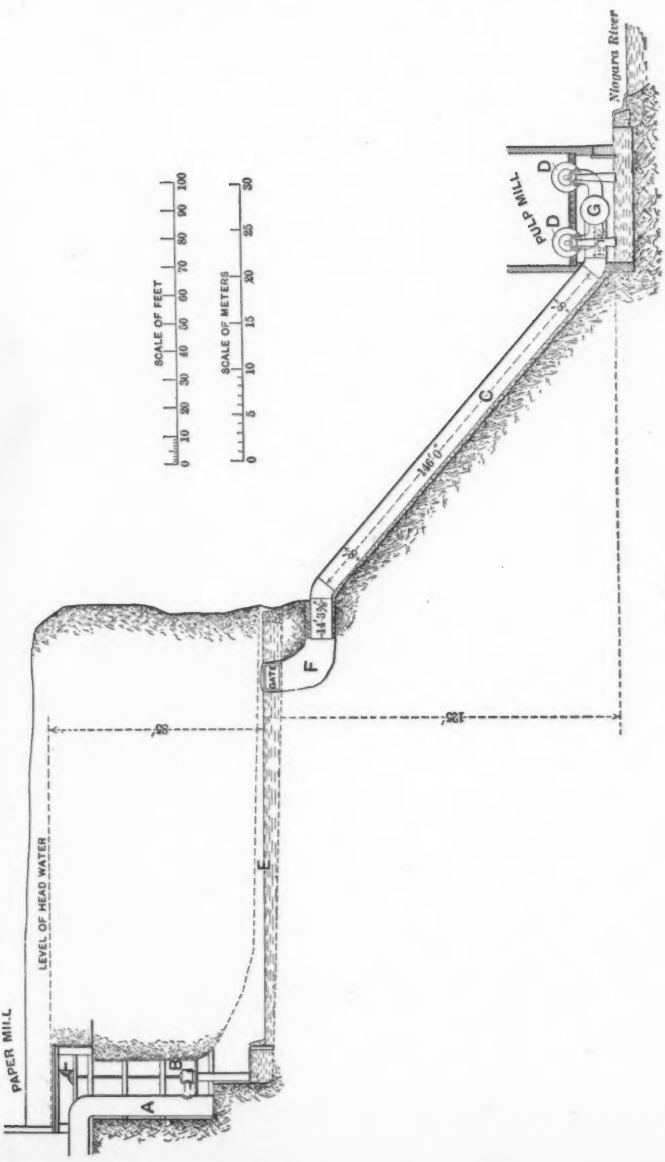

PAPER MILL
LEVEL OF HEAD WATER
A
B
E
F
GATE
C
146'-0"
PULP MILL
D
D
G
Niagara River
SCALE OF FEET
0 10 20 30 40 50 60 70 80 90 100
SCALE OF METERS
0 5 10 15 20 25 30

FIG. 2.

obtained from the full capacity of the canal. This was all used by the various mills shown on Fig. 1.

In 1892 the company commenced the enlargement of its canal by excavating an additional 35 ft. in width to a depth of 14 ft. This enlargement, which is now practically completed, gives a total capacity of upwards of 50 000 H. P.

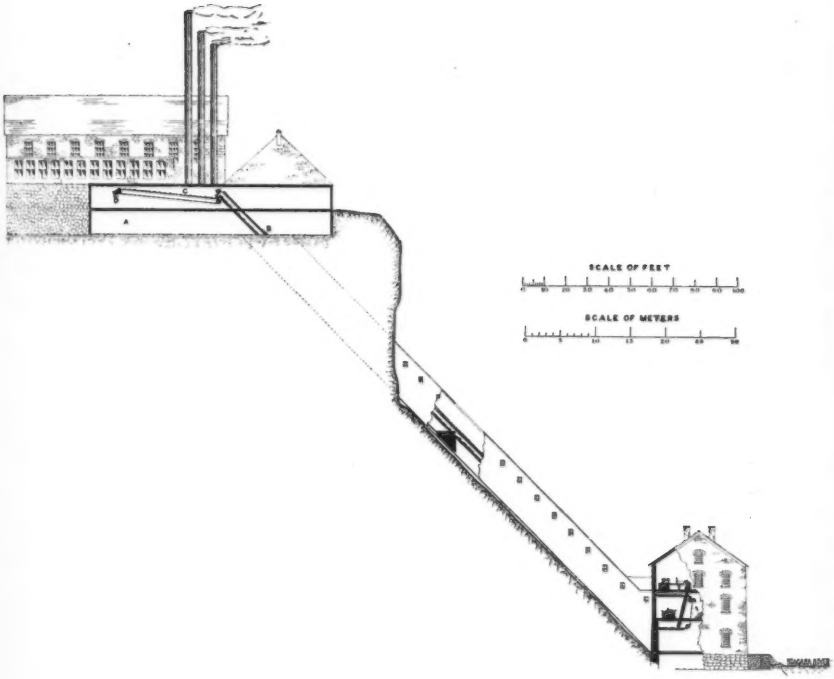
In the spring of 1892, the Cliff Paper Company became desirous of increasing their plant by adding a wood pulp mill, to use about 2 500 H.P. They leased sufficient water from the Niagara Falls Hydraulic Power and Manufacturing Company, and, not desiring to wait for the enlargement of the canal to be completed, they agreed to take it from the tunnel through which water was discharged from their pit, and the writer was called upon to design the plant.

For the purpose of getting the machinery requiring the largest power near to the wheels, it was decided to build a mill on the lower bank near the water's edge, and to place the pulp-making machinery in it, preparing the wood on the top of the bank, lowering it down ready for grinding and elevating the product.

The general design and working of the plant is shown in Plate XXIX. In the room *A* is placed the machinery for sawing the wood to the proper length and removing the bark. The logs thus prepared are placed upon a chain conveyor at the point *B*, carried down the incline into the grinding-room floor, in the mill below. The wood is ground on this floor and mixed with water and flows into a tank in the basement; from this point it is elevated by pumps to a tank in the roof, and flows from it on to the wet machines, where part of the water is removed, leaving it in the form of a wet, paper-like substance; from the wet machine it drops on to another conveyor (*C*, Plates XXX and XXXI) and is carried to the returning side of the same conveyor which brought down the wood, then carried up the incline to the second story of the mill above the bank, where it is dropped on to the belt conveyor *C*, and from there to another, *D*, running at right angles with the direction of the first conveyors, which carries it to the beating engines.

To divert the stream of water flowing through the tunnel (*E*, Fig. 2), and confine it for use in the new mill, a short tunnel (*F*, Fig. 2) was driven into the face of the bank at a point about 20 ft. below and 12 ft. to the left of the mouth of the old tunnel. The relative position of the two openings into the face of the bank is well shown on Plate

PLATE XXIX.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



XXXII, which is from a photograph taken during construction. The plan of the tunnel and its connection with the old tunnel is shown on Plate XXXIII.

From the mouth of the new tunnel, an iron pipe 8 ft. in diameter (*C*, Fig. 2), was laid along the slope of the bank connecting with the tube *G* (Fig. 2), 10 ft. in diameter, in the basement of the lower mill. From this tube the water is brought to the wheels on the first floor. Provision is made for the discharge of water into the tunnel direct from the canal in case the discharge from the wheels does not furnish a sufficient supply.

Owing to the contracted channel of the river below the mill there is an extreme fluctuation in the water below of about 30 ft. and it is liable to sudden changes. On this account the first floor, on which the wheels are placed, is set about 16 ft. above the ordinary level of the water in the river, which is above the highest recorded rise, the remaining part of the head being obtained by the use of draft tubes.

Work was commenced on this plant about May 1st, 1892. The first thing done was to trim off all of the rock on the face of the bank which appeared to be in danger of falling. Then a notch was excavated in the bank 12 ft. wide and to the depth of the dotted line Plate XXIX), and the tunnel was driven and the gate put in at its head.

During the time that the work was in progress the flow from the old tunnel, amounting to about 130 cu. ft. per second, could be stopped only on Sundays. This water was carried past the opening in a temporary flume, which it was afterward found necessary to extend down the slope of the bank for about 120 ft. (as shown on Plate XXXII) to get rid of the spray caused by the water tumbling down over the slope, which interfered with the work on the mill below.

The opening into the old tunnel is closed by a gate and protected by a rack shown in detail on Fig 3. The gate is operated by extending the shaft *A* along the roof of the tunnel to a hand wheel, near the point *B* (Fig. 2). The rock taken out from the tunnel and the notch in the bank was thrown down upon the slope on top of the débris which had been accumulating there for ages.

The next step was to clear the site for the building and to remove the loose material which might slide down. As the broken and disintegrated rock which had fallen from the cliff at various times lay at the "angle of repose," this clearing amounted practically to removing

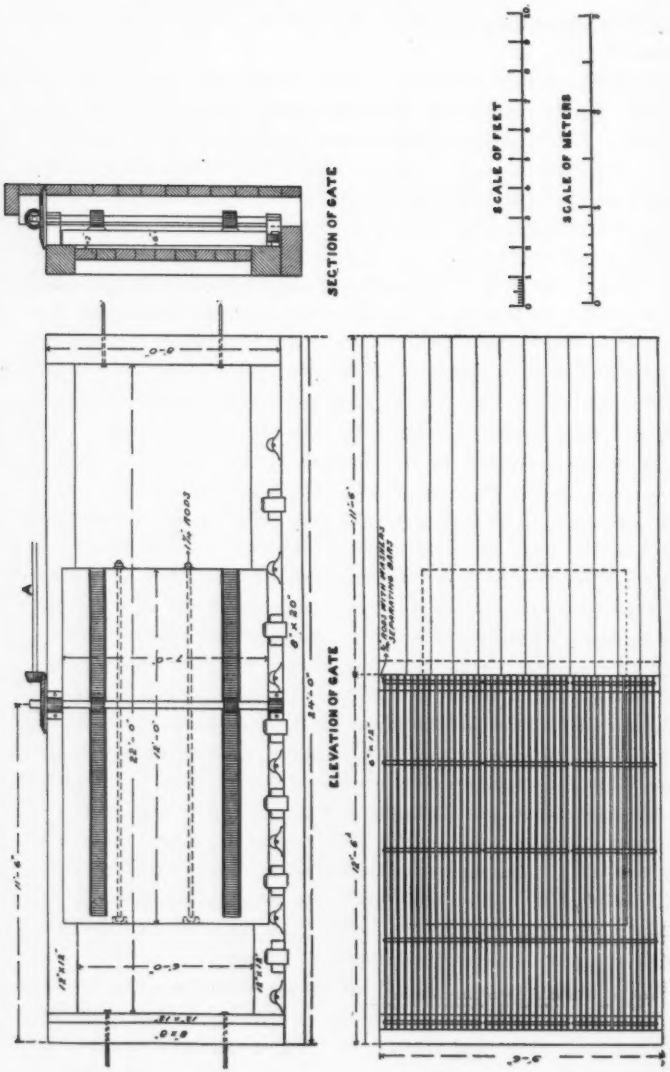
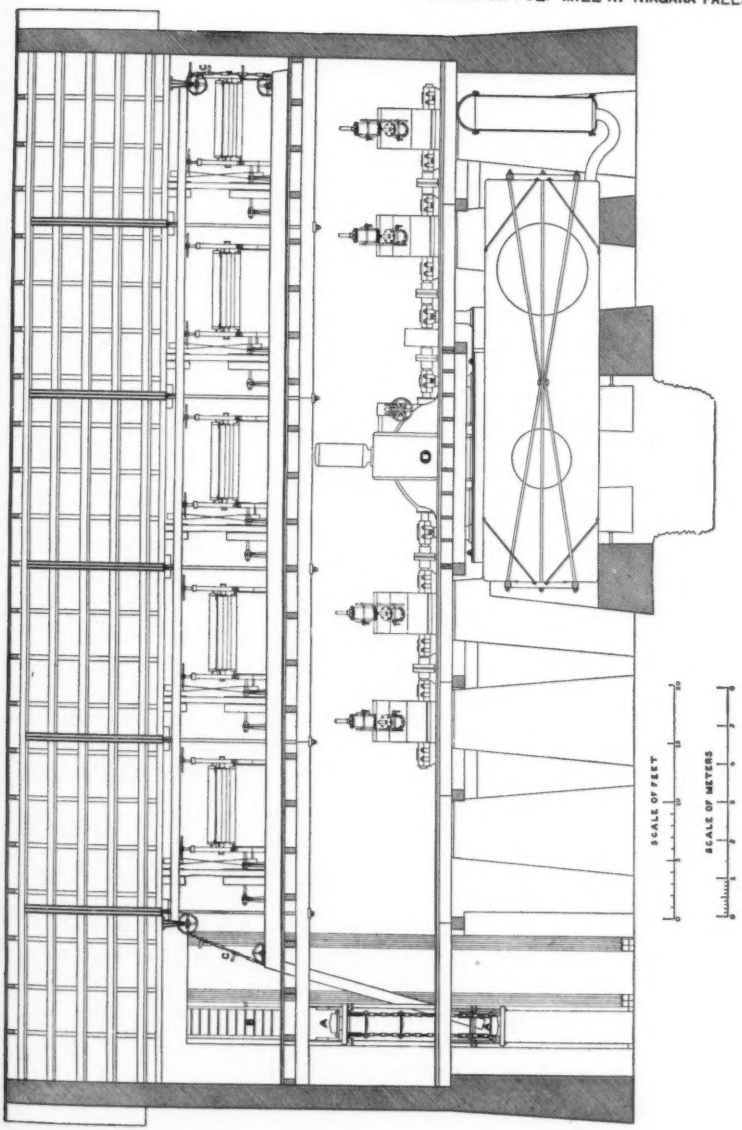

SECTION OF GATE
SCALE OF FEET
SCALE OF METERS
ELEVATION OF GATE
ELEVATION OF RACK

FIG. 3.

PLATE XXX.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



all the loose material from a strip about 100 ft. wide, running from the face of the cliff to the water. From the face of the cliff to a point about 80 ft. back from the water's edge, solid rock was found under about 5 or 6 ft. of loose material, and running down at practically the same slope as that on which the penstock pipe was laid and the incline building was built. At this point, 80 ft. back from the water's edge, the rock makes a vertical descent for about 70 ft. to a practically level bed of red sandstone at about the water's level. On top of this sandstone, to which it was determined to go for a foundation, over the entire mill site and about 40 ft. back from it, was loose material, varying from about 20 ft. deep, near the water's edge, to about 70 ft. deep at the back side.

This bed of loose material, which it was found necessary to remove, was composed of small stones, earth, large boulders and buried trees well soaked with water and ready to slide upon being disturbed. The walls were constructed of stone quarried from the large limestone rocks which had fallen from the cliff and lay upon the site. As there was no room for storing material, it was found necessary to get down to the foundation at an end of the building and start the walls as quickly as possible. The necessity for doing this interfered somewhat with the speed of the work of excavating and increased the danger from sliding; but, notwithstanding this, the site was cleared and the walls erected in about three months, without serious injury to any one connected with the work.

Near the center of the building a trench for the wheel pit was excavated into the solid sandstone, 14½ ft. wide and 6 ft. deep, from the cliff side of the mill to the water. This cut is seen in section on Plate XXX and Fig. 4. Across this opening the wall on the river side of the mill was carried by a stone arch. About 15 ft. outside the building on the river side a wall was built across this cut 6 ft. in height, to form a seal for the draft tubes.

As soon as the foundation was sufficiently built, the 10-ft. tube running lengthwise of the building across the wheel pit, as shown in Plate XXX, was placed in position, and the construction of the 8-ft. pipe leading from it to the tunnel was commenced. The 10-ft. tube and the lower 50 ft. of the 8-ft. tube were constructed of boiler steel $\frac{3}{8}$ in. in thickness, and all longitudinal seams were double riveted. The heads of the 10-ft. tube were constructed of the same material, strengthened

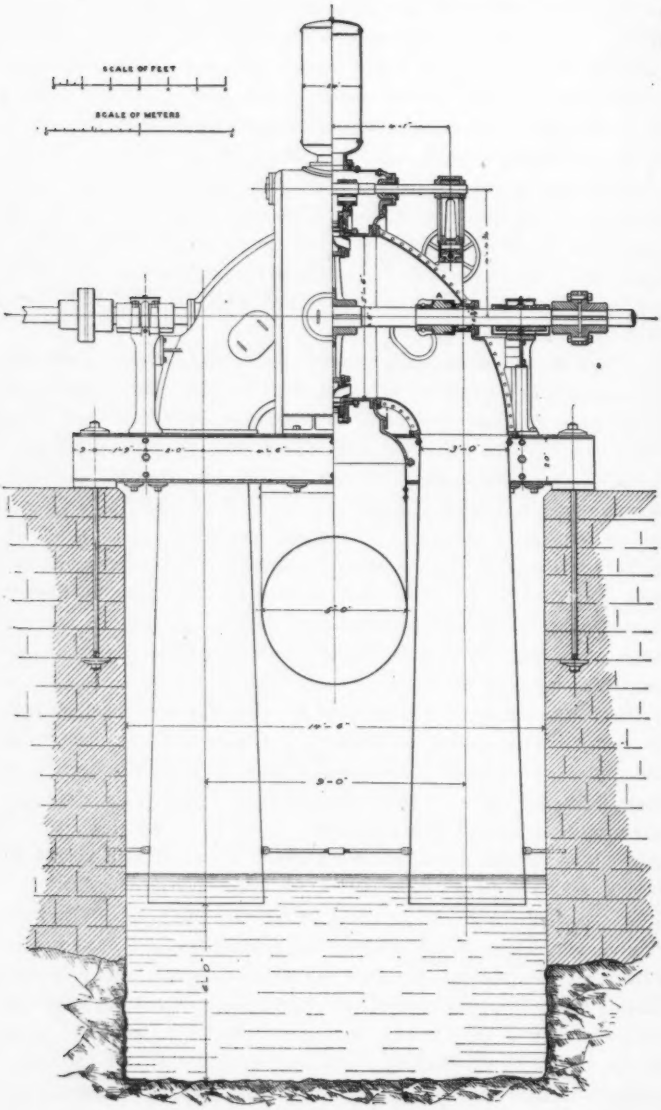


FIG. 4.

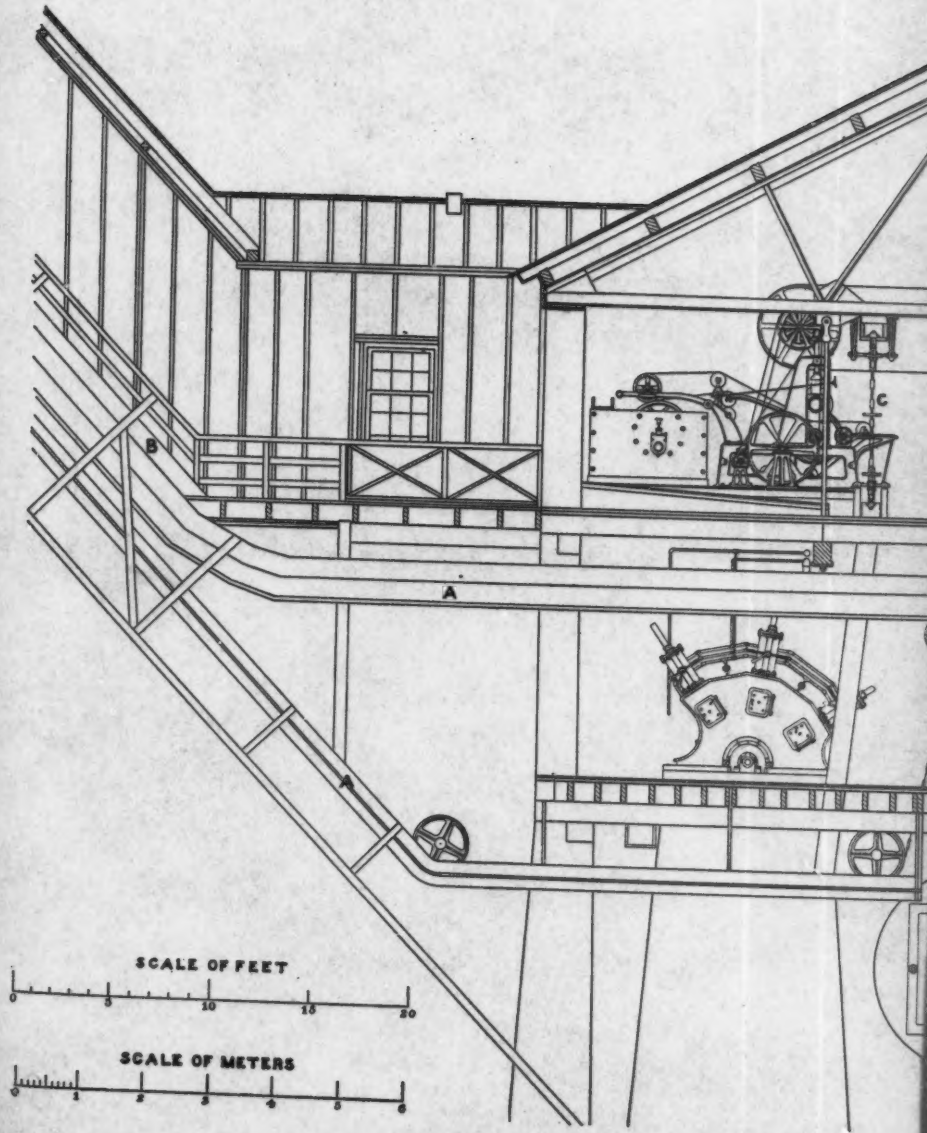
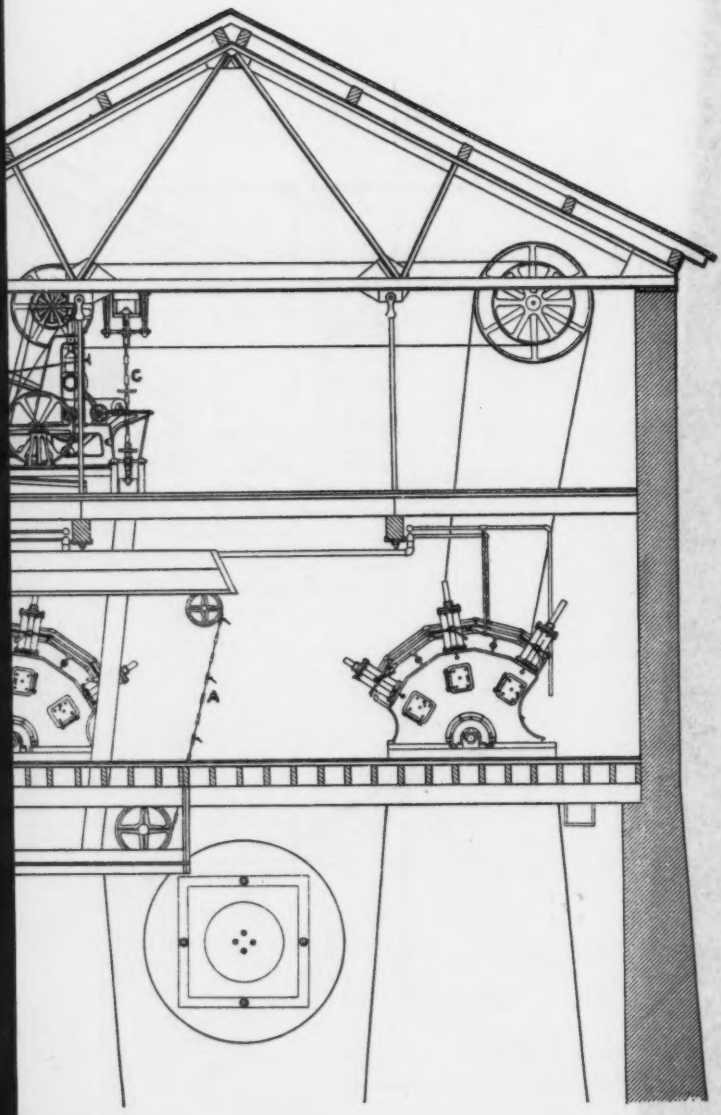

A
B
C
SCALE OF FEET
0
5
10
15
20
SCALE OF METERS
0
1
2
3
4
5
6

PLATE XXXI.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



by a wooden frame on the outside, through which four rods 1½ ins. in diameter were passed from end to end of the tube and gathered together in a bunch at the center, as shown in Plate XXX. The upper portion of the 8-ft. tube was constructed of $\frac{5}{16}$-in. boiler steel, single riveted. This tube was made in sections about 15 ft. in length at the shops and lowered down and set in place, and the connecting seams riveted on the site.

For the handling of this and other materials a steam derrick with a 75-ft. boom was erected on top of the bank, shown in Plate XXXII. Materials were lifted from the ground near the edge of the bank, the boom swung around square with it, the load lowered on to the inclined skidway below, and, still held by the derrick, were slid down to the level of the mill, where they were picked up by another derrick and swung into place.

The mill was closed in and the tubes placed in position, so that the interior work on the mill was carried on during the winter. The construction of the incline was delayed somewhat on account of the severity of the weather.

The interior arrangement of the mill is shown on Plates XXX and XXXI. It is two stories high above the basement, and the inside dimensions are 40 x 88 ft. The walls are built of stone quarried on the site as before described, laid in Union cement mortar. The basement walls are 7 ft. thick at the base, battered on the outside to 3 ft. at the level of the first floor to resist the pressure of the loose material outside. Above the first floor they are 2 ft. thick.

The roof and second floor are supported by steel trusses calculated to support a load of 40 lbs. per square foot on the roof and 200 lbs. on the floor.

All the machines on the first or grinding-room floor are supported on independent stone foundations built up from the solid rock.

This mill is connected with the buildings on the top of the bank by a building 10 ft. wide on the inside and 26 ft. high, constructed along the slope of the bank to the face of the cliff, and from there through the notch blasted out to receive it to the mill above.

Three feet in width of this inclined building is occupied by the conveyor for handling the wood and the pulp before described and shown at *A* (Plates XXX and XXXI). Directly over the conveyor are the stairs *B*, and underneath is a line of 6-in. pipe bringing water directly

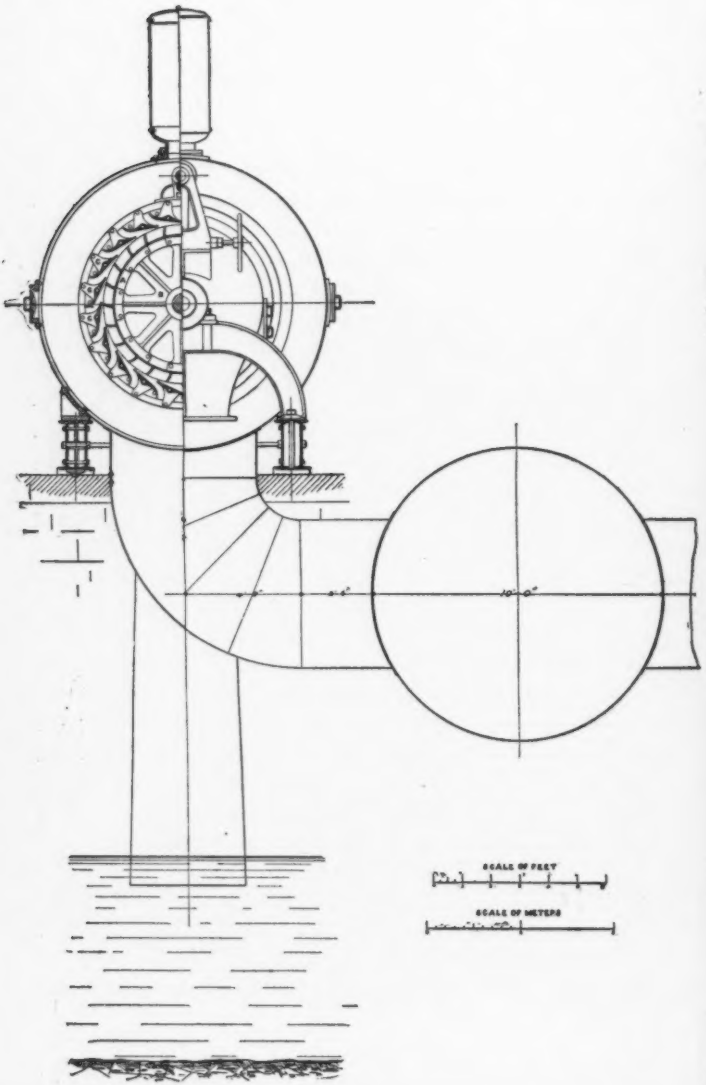
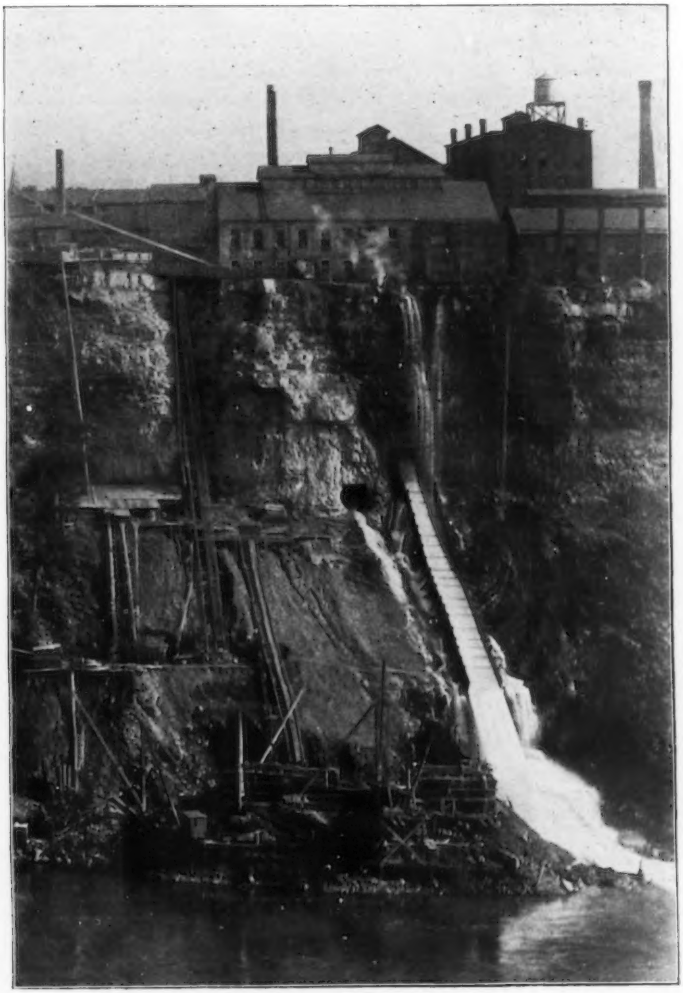


Fig. 5.

PLATE XXXII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



from the basin for supplying pressure to the grinders and for fire protection.

The balance of the room in this building is occupied by tracks on which a car for transporting men and materials is run. It consists of a framework of iron, built up high in front, so as to bring the floor level, and it is operated on the water-balance principle. On the outer pair of rails (Plate XXX) runs the car proper, and on the inner pair a tank car which is filled with water at the top, to draw the car up, and which is automatically emptied at the bottom. The car is also provided with a small tank, to be filled with water in case the load going down is light. The two cars are connected by three ¾-in. steel wire cables passing around drums at the top and controlled by brakes. At a point a little below the center, the inner track is dropped to a lower level, to permit the tank car to pass underneath.

The wheels are horizontal turbines, supported on steel I beams spanning the 14½-ft. wheel pit, and are set so that the center line of the shaft is 1 ft. above the floor. On each side of the wheel are two Mills pulp grinders, of the ordinary form, the shafts carrying the stones being coupled directly to the wheel shaft. All couplings are made with a plate between the faces, so that, in case of repairs being needed to any grinder, the bolts to the coupling between it and the wheel can be taken out and the plate removed, leaving the wheel to drive the others on the line so that an accident to one grinder will in no event stop more than two of the eight grinders in the mill.

On the right of the water wheel (Plate XXX) is a pulley, from which a belt drives the shaft hung on the bottom chord of the roof truss in the second floor, from which the pumps and wet machines are driven.

On account of the great expense involved in building, and the apparatus for measuring the large amount of power which would be developed by these wheels, the specifications were drawn calling for a wheel, horizontal in form, to run at a speed of 225 revolutions per minute under a head of 125 ft., and to develop sufficient power to grind 12½ tons of wood pulp, dry weight, per day of 24 hours, on four Mills grinders, using 24-in. wood, and to use not more than 7½ cu. ft. of water per second per ton of pulp per day. It was intended by these specifications to require an efficiency of about 75 per cent. Certain other requirements were added as to strength of parts, the whole design to be subject to the approval of the engineer.

Under these specifications a contract for the construction of one wheel was let to James Leffel & Company, of Springfield, O., with the option of taking a second wheel if the first proved satisfactory.

The wheels were designed by Mr. A. F. Sparks, engineer for James Leffel & Company.

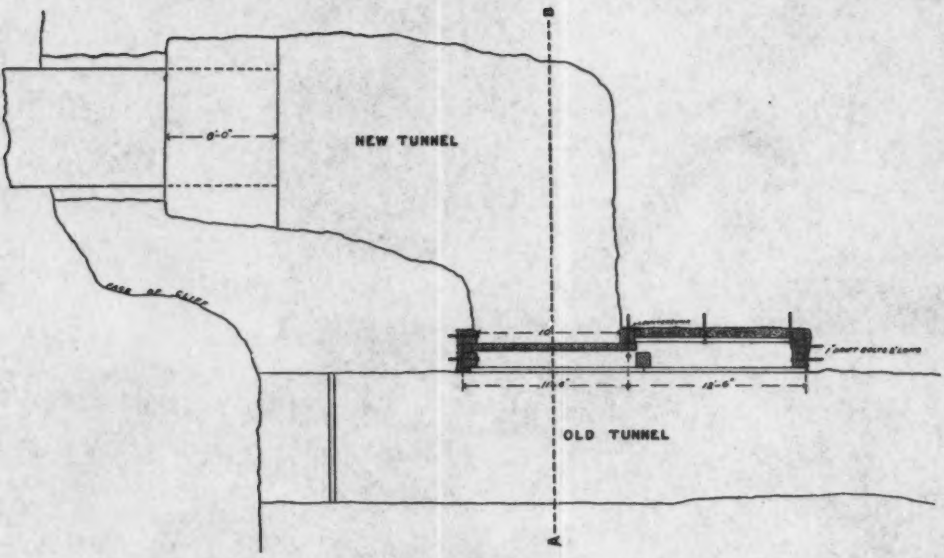
The wheel runners are 66 ins. in diameter. The bucket rings *A* (Fig. 5) are made of a special quality of bronze. These rings are fitted to a heavy cast-iron center *B* (Fig. 5) with steel bolts; each ring supplied with 24 buckets, with the discharge opposite each other. The wheel runner is fitted substantially with keys to the wheel shaft, which is made of hammered wrought iron, finished diameter through bearings $6\frac{7}{8}$ ins., with a total length from center to center of couplings of 17 ft. In order to prevent the wheel shaft from shifting endwise, suitable adjustable collar bearings are located on it, immediately on the inside of the elbow *A* (Fig. 4).

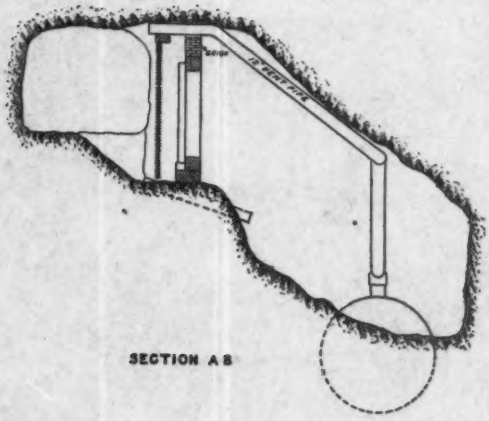
Surrounding the outside of the wheel runner are wheel cylinders, supplied with 20 gates *C* (Fig. 5). These gates are made of cast steel, and designed to be as nearly balanced at all points of the gate opening as possible. They are mounted on steel gate bolts attached to wheel cylinders. Each gate is supplied with two side-rack arms which arms are attached loosely to the two side-rack rings. These rings are mounted on the wheel cylinders, and are operated simultaneously by the movement of the gate shaft connecting to them with roller rings made of cast steel. The gate shaft is made of hammered wrought iron, passing through bronze stuffing-boxes in the sides of the cylindrical case. One end of this gate shaft is operated by a suitable lever, with bronze nut, steel screw and hand wheel for same, carried in the heavy frame, mounted on one of the elbows.

This work is contained in a cylindrical case 10 ft. diameter, by 4 ft. wide. The heads are made of heavy cast iron, with $\frac{3}{8}$-in. steel shell solidly riveted to them. On the top of the case is a large air chamber to assist in equalizing any irregularities in the flow of the water to the wheel. This air chamber is supplied with an air pump and glass water gauge, so that it can be cleared properly and filled with air when necessary. The case is also fitted with manholes and plates.

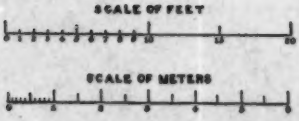
On each side of the case elbows are fitted, which are made of cast iron, being split through the center and bolted together, and where the wheel shaft passes through the elbows are stuffing-boxes with bronze glands. Each elbow is fitted with manholes and plates.

PLATE XXXIII.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.





SECTION A B



On the discharge end of the elbows are fitted draft tubes which are each 18 ft. long, made of ¼-in. steel, thoroughly riveted and caulked throughout. These draft tubes are substantially anchored to the foundation walls to prevent breaks or leakage by any movement. The wheel shafts, after passing through the elbows, are carried in heavy flat bearings, each 24 ins. long, lined with anti-friction metal, bored to fit the shaft, and supplied with ring oiling attachments, with large capacity of oil chambers at each end and on bottom sides of the bearings. These bearings are mounted on heavy cast-iron bridge trees, and are supplied with suitable bolts and adjusting screws, making a distance of 4 ft. from the center of the wheel shaft down to the top of the steel beams.

The work is mounted on four heavy 20-in. steel beams, of suitable strength and proportion for spanning the foundation walls, which are 14 ft. 6 ins. in the clear. The maximum fiber strain in the beams, due to the weight of the wheel and case when filled with water, was fixed by the specifications at 9 000 lbs. These beams are secured to the foundations by foundation bolts and anchors. Every precaution was taken in the selection of all materials for these wheels, and extra care exercised in the workmanship throughout.

By this design of the wheel, the water is brought to the wheel runner through one set of gates, each set of buckets handling one-half the water, discharging opposite and parallel with the wheel shaft, thus preventing any heavy or undue thrust on the wheel shafts.

The general arrangement is such that when necessary an examination can be given the inside of the cylindrical case containing the wheel case and the operating mechanism for it, also the inside of the discharge elbows containing the collar bearings, shaft and the discharge of the wheel runner buckets.

The first wheel, driving four grinders, was started and the manufacture of pulp commenced March 13th, 1893, and has run 144 hours per week since that date without any stoppage for repairs requiring more than a few hours.

On May 20th, 1893, a test was made to ascertain whether the wheel came up to the requirements of the specifications.

The wall across the outlet to the tail-race was built with a view to setting a sharp-edged weir on it. An oak timber was set into the top inner corner, to which a 3-in. oak plank with the top edge beveled off on the outer side was securely fastened with lag screws.

Timbers had been set into the masonry forming the sides of the tail-race, and a space about 8 ft. above and below the weir was sheathed with planed and matched pine boards, making a weir without end contractions. Close along the back of the weir 1-in. iron pipe was run, perforated with holes to admit air under the sheet.

A 2-in. iron pipe was run through the wall leading the water from a point about 10-ft. in front of the weir to a tank in which the hook gauge was placed.

The penstock pipe was tapped at a point near the tunnel, and an iron pipe was led over against the side of the incline building and up the side of the building to a point above the level of the head water, and topped out with a glass tube so that the elevation of the head water could be read off a gauge graduated to feet and tenths placed alongside the glass tube. The elevation of the zero of the hook gauge was carefully taken, and the length and elevation of the weir were carefully ascertained.

The experiment was continued for three hours. An observer was stationed at the head gauge and another at the hook gauge and simultaneous readings taken every five minutes. From the readings of the two gauges, the head acting on the wheel and the quantity of water discharged were calculated. The writer observed the speed of the wheels and saw that the weight of the pulp made was ascertained and recorded.

The result of the experiment showed that 2.085 tons of pulp were made during the three hours, equal to 16.678 tons per day. The quantity of water discharged was equal to 109.338 cu. ft. per second, reduced to a head of 125 ft., equal to 6.558 cu. ft. per second per ton of pulp per day.

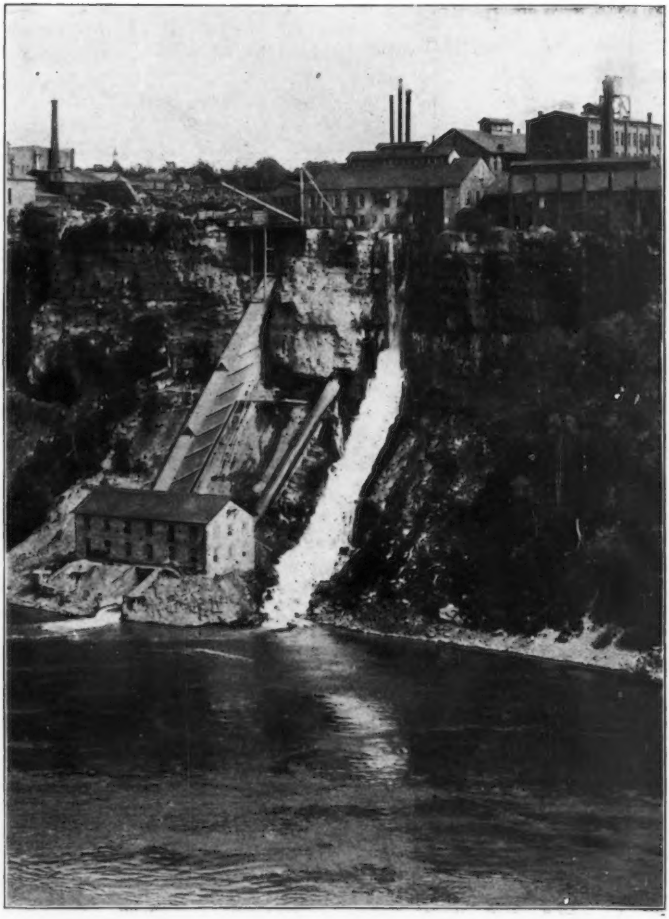
When the result of this test was reported, the wheel and machinery for the balance of the plant were at once ordered.

The second wheel was started December 15th, and has been running since and doing as good work as the first.

The excavating of the notch for the incline and the driving of the tunnel was done by contract. The balance of the work was done by day labor, under the immediate charge of Mr. C. H. Turver as superintendent, and much credit is due to him for good workmanship under many difficulties.

Plate XXXIV shows the mill completed, including the incline and the mills on top of the bank.

PLATE XXXIV.
TRANS. AM. SOC. CIV. ENGRS.
VOL. XXXII, No. 728.
JOHNSON ON PULP MILL AT NIAGARA FALLS.



DISCUSSION.

CLEMENS HERSCHEL, M. Am. Soc. C. E.—I had great pleasure yesterday in reading a paper by two young engineers, some features of which were similar to those of this paper, and I should be false to my sense of duty if I did not say something about the paper just read. We see here, as we did in that of yesterday, what I feel is a gratifying indication of the habits of the rising school of engineers, of engineers who go about testing, and putting in figures the results of their work. I do not know that I ever saw before the product of a mill reduced to the number of cubic feet that were expended in producing it. You will observe the specifications were drawn in that way. Here is a plan which, taken as a whole, consists of a great many parts, a mill on top of the bank, another below the bank, water-wheels, machinery to make pulp, etc.; but the object of the whole plant and all its expenditure is simply to make pulp for paper, and the thing to do it with is water; so much pulp to be produced, and so much water to be expended in doing it. Those were the specifications, and as you will observe from the tests, the specifications were more than complied with. As I said before, I would not be doing right if I did not express my own pleasure in the paper read, and I trust that I speak for the convention also.

J. T. FANNING, M. Am. Soc. C. E.—In relation to this method of determining the amount of power required for the unit of product of a given mill, I might mention that we have made measures of the water-power at some of the Minneapolis mills for a similar purpose. For instance, I placed a weir in the tail-race of the Pillsbury A Mill, the largest flouring mill in the country, and recorded the flow over the weir at least three times each day for a continuous period of six months. I had also the record of the daily product in barrels of flour of this mill for the same period of time, and thus had the information of the mean amount of power and the quantity of water under the given head that was required per barrel for the manufacture of flour in that mill.

The power used by five saw mills at Minneapolis was measured in a similar way throughout an entire sawing season, and the record made of the daily product in M feet of lumber of each mill.

The flouring and saw mills thus became meters indicating by the amount of their products the mean quantities of power and mean quantities of water, under the given heads, used in each unit of manufacture of their products.

W. C. JOHNSON, M. Am. Soc. C. E. (by letter).—In line with the remarks of Mr. Fanning I will say that, as engineer for the Niagara Falls Hydraulic Power and Manufacturing Company, I keep a record

of the quantity of water used by each mill. To ascertain this quantity, I make use of the wheel as a meter. Having once ascertained, by means of weir or other measurements, the discharge of the wheel at several different gate openings and under a known head, then by taking a daily record of the gate opening and the head acting on the wheel, the amount of water used can be readily computed.

With this end in view, a measurement of the water discharged at different openings of the gate by the wheel last put in was recently made. This wheel was made with a slightly larger gate opening than the first one. The discharge reduced to a head of 125 ft. was found to be 116.293 cu. ft. per second at full gate, 91.085 cu. ft. per second at three-quarter gate, 57.306 cu. ft. per second at one-half gate, 25.272 cu. ft. per second at one-quarter gate.

Gauges have been put on the wheels by which the proportional gate-opening can be read to hundredths, and other gauges by which the elevation of the head and tail-water can be read.

This furnishes the data by which the discharge of the wheels at any opening of the gate and at any head may be calculated.

A daily record is kept of the quantity of water used, and the Cliff Paper Company has a record of pulp made so that a computation of the water used, as compared with the pulp manufactured, may be made at any time.